JULY 1950

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This month C.E.P. begins the publication of the papers presented at the Industrial Waste Symposium held in Pittsburgh. A problem on the economics of waste disposal, and kind of treatment, and the selection of a suitable plant site with respect to waste disposal is answered in the papers of this Symposium which will be continued next month.

This month's Letter to the Editor tells of an unusual problem which mushroomed in a Brooklyn plant.

The Third World Petroleum Congress is to be held in Holland at the Hague in 1951. C. E. Kirkbride of Houdry Process at Marcus Hook, a member of the National Committee representing the American Institute of Chemical Engineers, will tell you all about it., i.e., a little more than we had space to tell you on p. 24.

Have you ever suffered from smog? You can have a free copy of a report on that problem in Los Angeles. Read about it on p. 26. Other book reviews of interest to chemical engineers contained in Marginal Notes.

J. J. Healy, Jr., comments this month on a public understanding of chemical engineering. Do you, as a chemical engineer, recognize your duty to the public so that the average person knows your importance to his economy. Read this month's editorial.

Never miss the Data Service. It's here again this month.

Keep in touch with activities of the Institute by reading the report each month of S. L. Tyler, Secretary. This month Mr. Tyler looks into the future a little and anticipates the publication of a 50-year history of the Institute.

The Classified Section this month lists openings for chemical engineers. There's one in New York State for the chemical engineer who can apply chemical engineering principles to production problems in batch process type of industry. Also, a leading firm in Philadelphia wants an engineer for development engineering on industrial process instruments. Another opportunity with a large insurance company awaits the chemical engineer.

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Number 7

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1950

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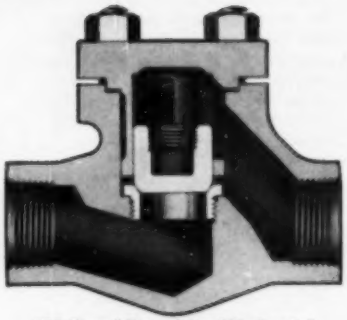

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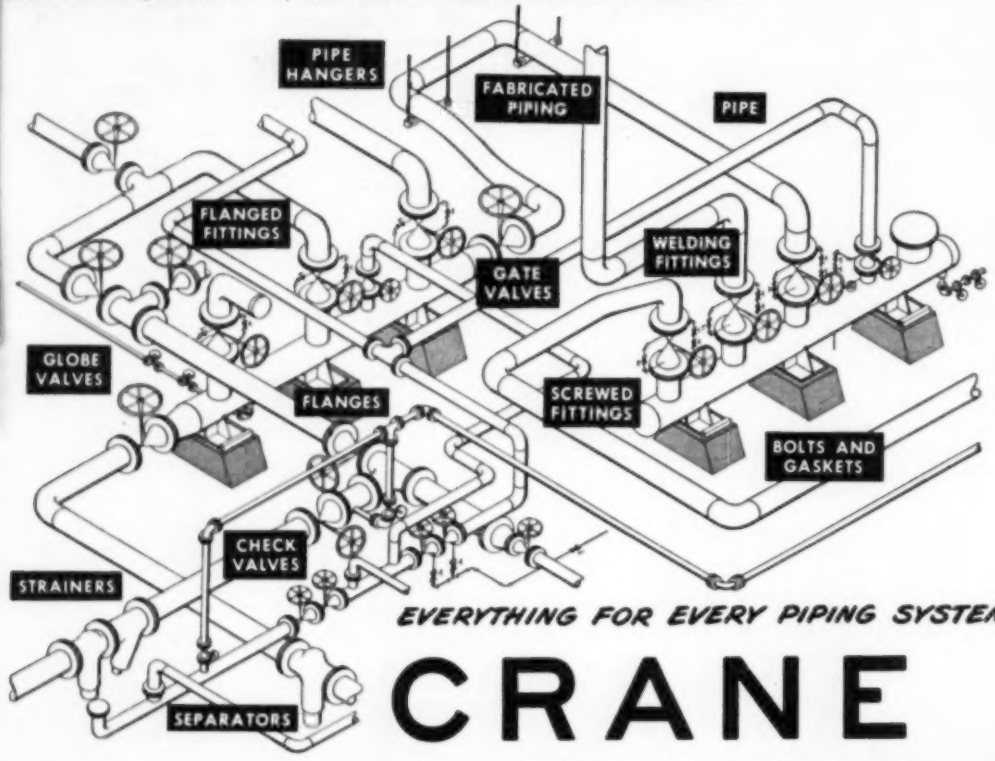

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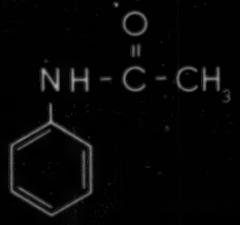

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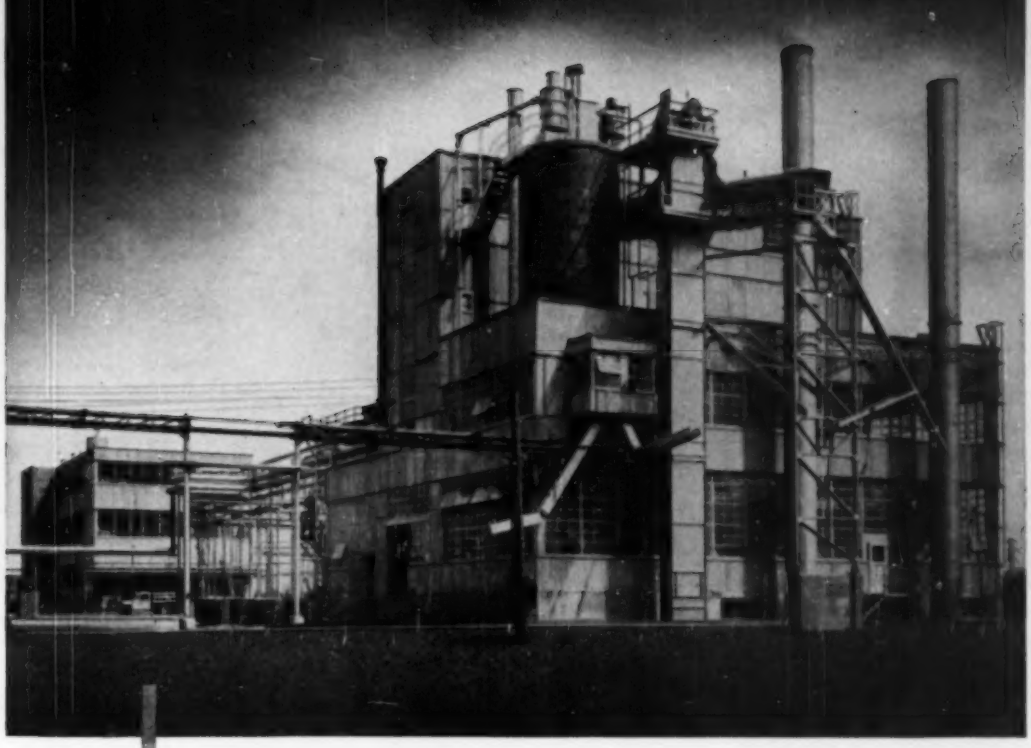

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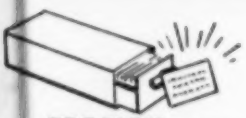

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OPINION AND COMMENT

ON UNDERSTANDING CHEMICAL ENGINEERING

"YOU cur," cried the duchess, "that's not chemical engineering!" The duchess was right in her realization that the technique in question, even though it was employed by a chemical engineer, was not chemical engineering. But perhaps the most amazing thing about her protest is the apparent fact that the duchess must have known what is chemical engineering in order to object to what it is not.

This is unique, for it is evident that public consciousness of what is chemical engineering and what the chemical engineer does is almost completely lacking.

For the recent Boston Regional Meeting the Public Relations Committee had at its disposal a store window in the heart of downtown Boston. The idea was that in this window could be displayed to a large section of the public an effective demonstration of the profession of chemical engineering. No demonstration was made because one which would effectively and conclusively say, "This is it," could not be conceived. Press reports of the technical sessions, in spite of the considerable effort made in press releases to stress the fact that this was a meeting of chemical engineers, gave credit to "chemists" for the advances in technology under discussion. A radio broadcast described ultrasonics and fluidization in such popular terms as "a method of whistling on a large scale" and "a man-made dust storm," true to a certain extent but hardly effective in improving any popular concept of chemical engineering.

This experience demonstrates the three difficulties that beset the problem of arousing the public mind to a realization of chemical engineering and its importance to our economy. In the first place, of all the branches of engineering, chemical engineering is the most difficult to present in conclusive form. A bridge, an automobile, an aeroplane immediately click as synonymous with the civil, mechanical, or aeronautical engineer. An oil refinery or a vitamin plant is a meaningless jumble of tanks and pipes. Not how it is done but what is the result is the important thing to the public.

In the second place, in presenting the result in terms of the product the part played by the chemical engineer is overshadowed often by the glamour of invention and discovery surrounding the chemist. "Eureka, I have found it," is generally accepted to mean "you can buy it now in quantity and at a reasonable price." It is definitely not realized that it is the job and the accomplishment of the chemical engineer to convert the test-tube cry of anticipation into the hard-boiled fact of daily profitable realization.

And in the third place, many chemical engineers probably do not see their profession in that light, either. How many of us keep well in mind that it is the objective and the duty of engineers constantly to strive to improve the standard of living. Do we understand that we are professional men because our objective is the public welfare, that we fail of our purpose and our right to respect if we cannot or do not use our technical training to produce more goods of better quality at higher wages and lower costs, and that of all professions, engineering, and particularly chemical engineering, because of the multitudinous possibilities of the chemistry with which it deals, is the only one which really contributes to an improved standard of living.

It is not stimulating to hear engineers complain bitterly that increased wage costs make processes unprofitable when the whole history of engineering has been to use improved technology to lower costs and increase wages. It is not encouraging either to hear chemical engineers suggest that the so-called labor problem will be solved by some philosophical approach which is inherent in technically trained men when their real approach is to translate their technological fundamentals into going plants which can be operated in a manner consonant with the dignity of man.

The application of detailed knowledge of the ramifications of pensions will not improve the standard of living. This and pensions, too, will come only from imaginative, forward-looking technology.

Public recognition of chemical engineers will come when chemical engineers themselves recognize their duty to the public and are articulate in expressing it. Then the duchess will not be alone in her understanding.

J. J. Healy, Jr.

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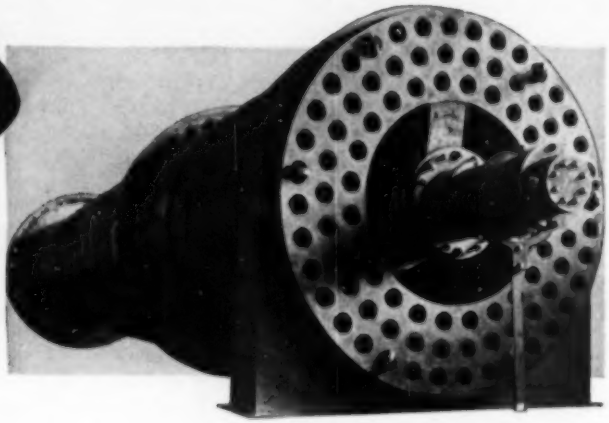

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Waste disposal confers benefits in triplicate for the plant wise enough to institute a thorough-going study of the problems . . . first it will have its house in order for the Federal program looking toward the abatement of water pollution . . . second by-products and a better understanding of the company production efficiency will be obtained . . . and most of all, a positive gain in community standing and respect will be forthcoming . . . beginning here is a series of articles for management and technical departments on some aspects of waste disposal for the chemical field. . . .

WASTE DISPOSAL

WASTE DISPOSAL AS A FACTOR IN PLANT LOCATION

F. W. MOHLMAN

Director of Laboratories, Sanitary District of Chicago, Chicago, Illinois

SEVERAL symposia have been held, by this Institute and by other societies, on the influences of transportation, fuel, water supply and quality of raw materials on selection of a plant site, but one of the most important factors, the suitability of site for waste disposal, seems to have been overlooked, although it may be of major importance in the choice of a site for a new plant. Since noting this oversight, it has seemed desirable to discuss the various factors which influence the choice of site for waste disposal, and to define the controlling factors which must be considered.

Many industries no longer have the opportunity to choose their sites and must adapt waste disposal to the capacities of the streams, lakes or harbors on which they are situated. Also for long-established cities, the opportunities for disposal of sewage are fixed, and depend upon the rate of growth of population and the stream flow, lake or harbor currents, or distance from the nearest communities. Various factors control the type or degree of treatment needed to satisfy conditions of disposal and usually these conditions can be met by industries more economically by salvage of polluting constituents or treatment of ultimate discharge rather than by relocation of the plant.

After salvage has reached an economic end point, treatment of residual wastes comprises various degrees or types of reduction, depending on what requirements must be met. Among these requirements are:

Neutralization of acid or alkali
Reduction of oil or scum
Removal of sludge-forming solids
Reduction of colloidal or soluble organic matter
Removal of soluble chemicals such as sulfides, phenol, cyanide, copper, chromium, iron, organic acids, antibiotics, or dyes

These requirements are largely in order of increasing complexity and costs, although a problem of removal of acid, oil or sludge may at times be more expensive, because of its magnitude, than the more complex process of reducing organic matter or toxic chemicals. However, the problems may be considered in the order listed, as follows.

Neutralization of Acid or Alkali

Neutralization of acid, alkali, pickle liquor, or mine waste is technically simple, although sometimes warranting study of economy and efficiency of chemicals to be used and disposal of sludge produced, if any. However, this is usually the simplest type of treatment required and should not demand too much study of agents available. When one thinks of the steel industry, chemical industry and mine wastes, the problem is discouraging in its magnitude and ubiquity, and this is why so much study has been devoted to attempts to recover acid, iron, calcium sulfate, or salable by-products rather than to be resigned to costly neutralization and disposal of a worthless sludge. These efforts may be suitable for large industries, but for small steel mills, chemical plants or acute mine waste problems, one must still depend on neutralization as a successful method for disposal of acid wastes.

Organic and Inorganic Acids. Organic acids, such as wastes containing acetic acid, other aliphatic acids (not greases), phthalic acid, malic acid or phenol, constitute another problem. Neutralization does not eliminate the oxygen requirements of these acids and thus does not reduce the B.O.D., but rather makes it more immediately active. Thus these acids are not in the category of neutralizable wastes but constitute some of our most troublesome organic pollutants, thus requiring large stream flows for disposal, if organic matter is not reduced by biological oxidation before discharge.

Inorganic acid wastes are a problem in many states, particularly Pennsylvania, or wherever steel mills are prevalent. In the Calumet Region of Illinois and Indiana, many tons of pickle waste are discharged to the rivers rather than to our sewage treatment works, where the iron clogs diffuser plates in the activated sludge tanks. In the rivers, there is enough alkalinity to neutralize the acid and iron oxidation does not amount to a high B.O.D. Therefore, in the Sanitary District of Chicago pickle liquor waste disposal is not considered one of the major industrial waste problems, and for the present such wastes are permitted to go to the rivers.

However, this is an example of fitting wastes to conditions of disposal. If the rivers had very low alkalinity, which would not equal the acidity discharged, many additional problems might be created. Thus Nature can be thanked for Midwestern alkaline surface waters, when it comes to disposal of acid wastes.

Reduction of Oil or Scum

Oil refineries create large problems in prevention of oil losses, with attendant difficulties. However, modern skimming methods are comparatively simple, aside from the size of basins required because of the tremendous volume of water used per refinery, mostly for cooling and condensing purposes, with

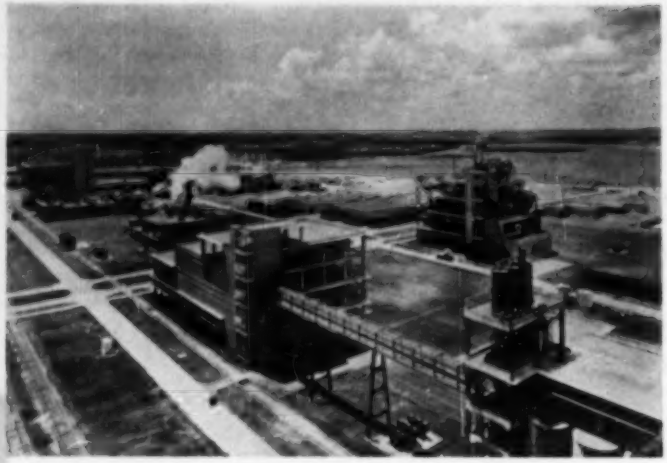

Fig. 1. Bluebonnet Plant, Corn Products Refining Co., Corpus Christi, Tex.

only minor volumes used for actual washing of crude oil or refined products.

The modern A.P.I. separator is efficient, even though no Raschig rings, cones, rupture plates, or bales of straw are used in vain efforts to increase recoveries. However, the detention period required to effect flotation requires large basins and removal of oil and sludge add to the expense. Some examples of A.P.I. basins will be discussed later.

Removal of Sludge-forming Solids

Plain settling and removal of *inorganic* suspended solids is simple as it requires only a concrete tank and provision for removal of inert solids. This procedure may be transferred to rivers if dredging is available, thus obviating all treatment at the plant.

When *organic*, putrescible solids are settled, they must be digested or dewatered at once, in order to prevent odors, and the treatment process becomes more complicated. This is a problem for sanitary engineers familiar with the principles of biological digestion of sewage solids. Sometimes this problem of disposal can be troublesome and costly, for example in the case of antibiotics wastes, food-products wastes or packing-house wastes, even though conditions of disposal permit discharge of the waste after a short period of sedimentation.

Reduction of Colloidal or Soluble Organic Matter

When the B.O.D. of clarified waste must be reduced, the problem of treatment immediately becomes more complex and more expensive, and chemicals, biological stone filters, activated sludge or sand filters must be considered. The cost of treatment immediately jumps and may be double the cost of plain sedimentation, even including sludge digestion. Here is a really complex problem, one which may warrant operation of a pilot plant to determine the capacities of biological or aeration devices used, and to preview the efficiencies obtainable by the use of such devices.

TABLE 1.—TYPE OF TREATMENT AS AFFECTING STREAM CONDITIONS
DISPOSAL OF FIVE TONS PER DAY OF FIVE-DAY B.O.D.

(Equivalent to City of 60,000)

Minimum Stream Flow cu.ft./sec.	No Treatment Stream Condition	Treatment and Conditions	
		Type of Treatment	Stream Conditions
1000	Excellent	None—Reaeration	Excellent
500	Good	Screening	Excellent
300	No fish	Sedimentation	Good; fish life
100	Odors, no fish	Sedimentation	No odors; fish doubtful
50	Heavy pollution	Chem. Pptn. High-rate Filter	Fish doubtful Fish life; good stream
25	Intolerable	Std. Rate Filter Act. Sludge	Excellent; fish life

This is where conditions of disposal begin to tighten up and when one must look critically at stream flow, composition of water in the receiving stream or lake, and continuity of service of the biological treatment device selected. One enters now the field of oxygen relations, and who is to say how much B.O.D. must be removed, how much contribution may be expected from stream or lake reaeration, and how nitrogen and carbon relations may affect the problem. These questions need a lifetime study for proper evaluation, yet the chemical engineer often tosses them off lightly. However, industry must face such decisions and must be prepared to evaluate the factors which determine the degree of treatment necessary, whenever dilution conditions demand a higher degree of treatment than screening or settling.

Degree of Treatment Required. When the load of organic matter in a waste must be discharged into the nearest stream, one must study the stream conditions almost to the same degree that one studies the possible degrees of treatment of the wastes. One is now working in the field of oxygen balance and must consider the effects of flow volume, reaeration, B.O.D., sludge removal and possibly bacterial concentrations as affected by the waste discharged. Then consideration must be given to oxygen balance, bacterial standards, and biological standards for the stream-bed, and recreational uses in deciding how much treatment will be necessary to provide satisfactory conditions.

Adjustment of the oxygen balance is necessary for most of these requirements. It is of course well known that in the absence of dissolved oxygen, putrefactive conditions give rise to odors, death of fish and absence of all normal biological stream conditions. These conditions are the results of pollution, but their removal may be necessary to various degrees, depending upon the type of treatment adopted.

Abatement can be carried to various degrees, viz.,:

a. Prevention of nuisance; dissolved oxygen less than 1.0 p.p.m.
b. Fish life permitted; D.O. more than 4.0 p.p.m.
c. Normal stream biology restored; D.O. 6.0 to 8.0 p.p.m.
d. Stream suitable for bathing; standard is coliform index.

The oxygen balance may be illustrated for a given pollution load and various stream flows, as shown in Table 1. This hypothetical condition comprises a load of 10,000 lb. of 5-day B.O.D./day, or the equivalent of 60,000 population. The minimum stream flow controls the degree of treatment needed, and usually

this refers to the low month of the year, not a daily minimum.

With 1,000 cu.ft./sec., no treatment is required and normal stream conditions obtain, as the dilution is 16 cu.ft./sec. for 1000 population, far above critical conditions. This criterion, flow in cubic feet per second per thousand population, is only a rough sign of dilution, once considered infallible but now seldom used, to define the dilution necessary. Actually this table has been worked out by consideration of oxygen balance, using minimum summer D.O. of 8.0 p.p.m. and various degrees of removal of B.O.D. by types of treatment. Also reaeration has been considered, an often-neglected asset in evaluating a stream's capacity for receiving pollution.

The flow can be reduced to 500, then to 300 cu.ft./sec., before any treatment except screening, to remove visible solids, should be necessary. At this dilution, i.e., 300 cu.ft./sec., sedimentation should be considered and adopted if assurance is necessary that fish life and normal bottom conditions should obtain. At 100 cu.ft./sec., sedimentation is needed, with assistance of reaeration, to prevent nuisance, and fish life may be doubtful. However, when the minimum flow is only 50 cu.ft./sec., one must have at least chemical precipitation, with 70% reduction of B.O.D., or high-rate filters, with 80% reduction. Finally, with a minimum flow of only 25 cu.ft./sec., the highest practical type of treatment available will be required, but if this is successful, giving 90% B.O.D. reduction, conditions should be excellent and fish life will not be wiped out by critical summer conditions.

These relations explain why pilot plant studies may be necessary for certain wastes, to determine the suitability for, say, chemical treatment, high-rate filters, standard filters or activated sludge. The type of treatment is not selected merely as a matter of choice—it is dictated by the dilution available. This principle applies to sewage disposal, and is equally cogent for industrial wastes. Certain other requirements sometimes require bacterial removal, and in this case the use of chlorine is preeminent. It may be necessary for any type of effluent and frequently is applied to settled effluents as at Buffalo or Detroit, but usually these requirements are found where the effluent enters a lake or harbor, although sometimes stream disposal also includes chlorination, if downstream water supplies or beaches are involved. In such cases, standards rest largely upon the permissible maximum coliform index (coli-aerogenes per 100 cc.) which varies from 500 to 3,000 according to the ruling of the local authority. Even the U. S. Public Health Service will give no maximum limit for safety, and many cities (New York, Chicago, Cleveland, Los Angeles) allow indices of 2,000 for specified percentages of samples. The Northwest, however (Portland, Seattle, etc.) unrealistically out of step with the rest of the United States, demands maximum indices of 50. These variations occur because of the lack of data connecting maximum coliform index and incidence of water-borne disease.

Industrial waste pollution is of course not concerned with this coliform index, unless the organic matter in the waste interferes with chlorination of a water supply and allows the coliform group to escape chlorination because of rapid fluctuation in chlorine demand and use of applied chlorine for oxidation of the organic matter rather than killing pathogenic organisms. This may, however, be an important consideration in industrial waste disposal, as discussed herein.

Removal of Specific Chemicals

Special problems are created by many chemical wastes, which are usually solved by treatment at the industry to destroy the objectionable constituents. These include sulfide, mercaptan, cyanide, phenol, chromium, iron, antibiotics or dyes, which may be amenable to destruction in low volumes and thus can be prevented from interfering with sewage-treatment plants or entering streams or lakes used for water supply.

Sulfides or mercaptans are removed by aeration, cyanides by acid, aeration or chlorine treatment, phenol by quenching coke, the Koppers vapor process, or light-oil extraction, chromium by treatment with ferrous salt and precipitation with lime, iron by recovery in large steel plants or precipitation with lime in smaller plants, antibiotics by special biological treatment; also dyes by expensive chlorine and lime treatment if authorities demand color removal, usually only an aesthetic consideration.

Thus specific treatments are available for these special cases and oxygen balance (except for phenol or antibiotics wastes) is not a factor to be considered. In the case of phenol and cyanides, minute amounts are objectionable. As little as 5 p.p.b. of phenol can create an objectionable taste in chlorinated water supply, and less than 1 p.p.m. of cyanide can kill fish. Thus wastes containing these substances must be freed of their toxic or taste-producing properties, and such necessities must be recognized in the location of chemical plants.

Specific Examples of Waste Problems

Contact with many waste problems warrants discussion of the solution of such problems for specific industries, or steps taken to alleviate the worst effects of pollution by industrial wastes by various methods of abatement of objectionable constituents. Degree of dilution often is the controlling factor and how to utilize such dilution is a necessary requirement in solving problems of waste disposal.

Reaeration. Application of the principle of oxygen balance may obviate all necessity for artificial treatment of wastes. At the new Bluebonnet plant of the Corn Products Refining Co. (Fig. 1) at Corpus Christi, Tex., wastes are minimized first by new techniques in plant operation such as use of surface condensers, ion exchange and other modern equipment. The wastes are free from suspended matter, but have solids in solution which have a certain B.O.D. These wastes were merely diverted from an enclosed area of limited extent behind a proposed breakwater, to the north and out into Nueces Bay, which has an area of 5 by 8 miles and almost unlimited opportunity for reaeration (with reference to B.O.D. of the waste). Thus by installing a sewage-treatment works for the sewage of the employees, and use of the oxygen content of the bay, natural reaeration may be invoked to stabilize the organic matter in the industrial waste, and thus obviate installation of high-rate filters or other type of biological oxidation. In this case, location on a large brackish bay, not used for water supply, was fortuitous for disposal of wastes.

Organic Acids. Organic chemicals from the Quaker Oats Co. at Cedar Rapids are also oxidized by the dissolved oxygen content of the Cedar River, which even at minimum flow retains sufficient oxygen to dispose of these soluble constituents without appreciable depletion of the dissolved oxygen. Here again, a river with enough natural minimum flow, has provided a safe means of disposal for an industry's wastes.

Antibiotics. However, antibiotics wastes are not always located on streams of adequate flow. Four such plants have been studied by the author for six months to a year each. Abbott at North Chicago discharges penicillin wastes into Lake Michigan and so far has satisfied authorities by use of settling basins and heavy chlorination of wastes discharged to Lake Michigan. Lederle, at Pearl River, N. Y., is making history in the antibiotics field with its aureomycin, and has recently installed a high-rate filter to pretreat its wastes before treatment at the municipal trickling filter plant. Thus the Lederle effluent need not be of the minimum B.O.D. neces-

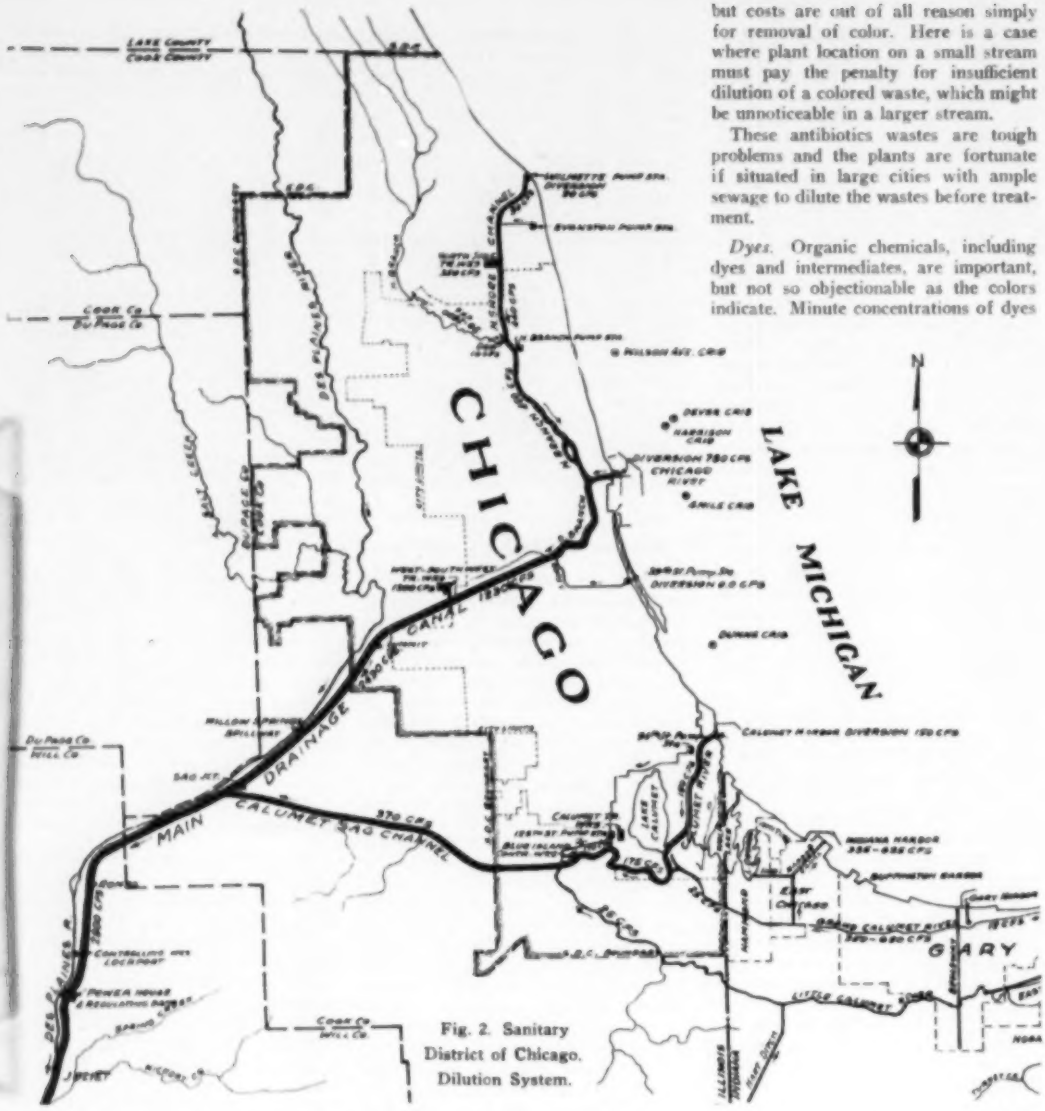

Fig. 2. Sanitary District of Chicago. Dilution System.

sary for final discharge into a stream of limited flow, but only partial treatment is necessary. However, the solution of the problem has been complicated by the rapid expansion of production and the unknown character of the waste to be treated. One of the essential steps in treatment of penicillin wastes, demonstrated by work in our laboratories, comprises aeration from one to four hours prior to application to trickling filters. Also a high degree of recirculation has been shown to be necessary, even up to nine to one, in order to reduce the strength of the liquid applied to the filter and to seed it with aerobic bacteria.

These principles were applied to the penicillin-treatment waste disposal plant of the Upjohn Co. at Kalamazoo, Mich., but here complete treatment is necessary as the waste enters a small stream with little dilution and a high-grade effluent is required. The loading on the filter is around 1500 lb. B.O.D./acre foot, and over-all reduction in September, 1949, was from 1650 to 109 p.p.m., or 93.4 per cent.

Another plant making streptomycin has had to apply tremendous quantities of lime and chlorine, at heavy cost, to decolorize the wastes and permit them to be discharged to a small stream. The decolorization is quite an achievement but costs are out of all reason simply for removal of color. Here is a case where plant location on a small stream must pay the penalty for insufficient dilution of a colored waste, which might be unnoticeable in a larger stream.

These antibiotics wastes are tough problems and the plants are fortunate if situated in large cities with ample sewage to dilute the wastes before treatment.

Dyes. Organic chemicals, including dyes and intermediates, are important, but not so objectionable as the colors indicate. Minute concentrations of dyes give noticeable colors that are visible but odorless and of no particular objection in many locations. The major requirement is that the organic matter be low enough to have little effect on the dissolved oxygen of the stream and that sulfides be removed as far as possible at the plant. These requirements are met by the National Aniline Co. at Buffalo by salvage operations within the plant and by diversion of certain wastes to the city sewage treatment works. Also acidities are neutralized by use of many tons per day of calcium carbide alkaline residue, a process also in use by the Calco Chemical Co. at Bound Brook, N. J. The latter company has an enor-

mous area for mixing varicolored wastes and discharging an effluent of fairly uniform brown color, neutralized to pH 4.5 by addition of alkaline wastes from Johns-Manville. However, residual B.O.D. is still a problem.

Phenol. There are eight by-products coke plants in the Chicago area, of which three discharge ammonia-still wastes to activated sludge sewage treatment works, one uses wastes for coke quenching, one has Koppers extraction plants and three have light-oil extraction plants. When suitable, biological sewage treatment will destroy the phenol if wastes are present in low enough concentration, but the wastes have a positive B.O.D. and add to the treatment load substantially. Therefore they cannot be allowed to overload an activated sludge plant.

The Koppers and light-oil processes easily remove 90% of the phenol and then if the residue can be treated with sewage, the removal is complete and satisfactory. However, where extraction alone is available, effluents still contain several hundred pounds of phenol, and this must be evaluated in relation to stream flow available, so that the phenol will average less than, say, 10 p.p.b. if the water is used for water supply. If, on the other hand, the concentration is higher, one must depend on the use of activated carbon to adsorb phenol and prevent obnoxious tastes.

Coke quenching is even less efficient than extraction for removal of phenol and such plants are slowly being changed to extraction plants. However, first costs are now enormous for an extraction plant, running up to or exceeding a half-million dollars; therefore installation is at a standstill. The new German solvents do not seem to appeal to American practice.

Oil. Oil separation is dependent on fairly simple devices which are only large-scale applications of catch-basin detention, but the efficiency of standard separators depends largely upon the physical condition of the waste-liquor influent. When emulsions are frequent and cannot easily be broken, the effluents may carry much more oil than normally, thus increasing the losses. Many public authorities have considered it possible to hold oil contents down to 15 p.p.m., but this seems unrealistic to this author who believes the requirements should be less rigid.*

Refineries have other problems—sulfides, mercaptans, phenol and other substances present in wastes, which are not removed by the simple action of separators. Biological treatment methods are necessary for such wastes, which should be kept out of the general effluents, as far as possible, and treated by more complex methods than the merely gravity flotation principle of A.P.I. separators.

* AUTHOR'S NOTE: Some authorities believe that requirements will be even more stringent in the future, demanding 5 p.p.m. and less.

Regional Problems

Some larger concentrations of industries have created problems of waste disposal which affect large areas or river systems and create national or international problems. Among these are (1) the influence of industrial wastes on the treatment requirements of the Sanitary District of Chicago, which has had frequent legal brushes with surrounding lake states and Canada, (2) the Calumet Region in Indiana, still under orders of the U. S. Supreme Court to abate industrial and municipal pollution of Lake Michigan, (3) Buffalo and the Niagara Frontier, now the object of investigation by the U. S. and Canada, under the International Joint Commission on Boundary Waters, which just concluded similar investigations at Detroit. These problems are here briefly discussed.

The Sanitary District of Chicago. Industrial wastes are a large factor in the treatment and disposal requirements of The Sanitary District of Chicago (Fig. 2) because they constitute a population equivalent, based on B.O.D., of 3,300,000 added to a human sewage load of 3,960,000 persons, with reference to disposal requirements. The situation is fortunate for industries, in that the cost of treatment of the industrial wastes is considerably less, proportionately, than the relations based on B.O.D., which do control the needs for dilution under Chicago conditions. The amount of dilution is about 1 to 1 or only about 0.2 cu.ft./sec. per thousand population for the total load, but this total load will be reduced 90% by activated sludge treatment, thus making the ratio about 2.0 cu.ft./sec. per thousand population, still inadequate to assure a high-grade river in the Des Plaines-Illinois System.

However, many studies of some 24 types of industrial wastes have been made by a crew of 15 men or more, over the past 15 years, and exact information is available to indicate the liability of each industry for flow, B.O.D. and suspended solids treated at the various sewage treatment works of the Sanitary District.

Here, if charges are applied, the industries may still consider themselves fortunate that their wastes can be treated in city sewage works, and that they can be discharged into city sewers instead of directly into streams, with cost of abatement borne by industry alone.

The Calumet Region. The Calumet Region of Indiana is an outstanding example of waste abatement by industry, when under the shadow of an order by the U. S. Supreme Court. Some five years ago, the state of Illinois brought action against the state of Indiana, seeking to abate long-standing pollution of the southern end of Lake Michigan by wastes from the Calumet Region in Indiana. This was later split into action against the cities and some 20 industries, of which 12 are most important.

The physical layout of the region is shown in Figure 3. The waterway affected by industrial wastes is the Grand Calumet, a sluggish stream originally almost dry in summer, but now with an appreciable flow induced by diversion of about 600 cu.ft./sec. at Gary by the Carnegie-Illinois Steel Co. Most of this water is used for cooling rolls and is not polluted, but pollution is introduced by the sewage of some 12,000 employees and residues of by-products coke wastes, after being used for quenching coke from some 19,000 tons of coal/day.

The flow travels west, to the junction with the Indiana-Harbor Ship Canal, and thence mostly toward Lake Michigan, with about 20% flowing toward Illinois through Hammond, joining the Calumet River and flowing down the Little Calumet toward the Illinois.

The flow to the lake is augmented by wastes from the treated sewage of Gary, East Chicago, Hammond and, now, Whiting, and in addition by wastes from the 12 industries shown in Figure 2, consisting of four oil refineries, four steel mills, and four organic chemical plants.

The industries started to comply with the Court's orders in 1945 and by 1949, the expenditures listed in Table 2, had been made. The first requirement was to construct sewers to discharge human sewage to existing or new treatment works. Then new A.P.I. oil separators were installed, for three refineries with capacities of about 200,000, 85,000 and 35,000 bbl./day. The first has a capacity of 110 million gal./day, the second, 10 million, and the third, 3.6 million. The reduced size of the second and third installations is due to recirculation of cooled water, thus greatly reducing the volume to be treated.

The fourth refinery, very small, has for many years had the only A.P.I. separator in the Chicago area.

Steel mills have Koppers and light oil phenol recovery and the Carnegie-Illinois uses the wastes for quenching coke. Pickle liquors are lagooned or discharged slowly into large volumes of water. The river is therefore not acid.

American Maize has "bottled up" its organic wastes, similar to the Corn Products procedure, and only a minimum residue goes to Lake Michigan. This abatement should remove one of

Fig. 3. Calumet Region. Industries and Dilution System.

the most troublesome features of the former pollution—namely, the occasional drifting of "slugs" of organic matter to the intakes of water supplies, followed by sudden increase of chlorine demand, sometimes too rapid or too concentrated to allow sufficient increase of chlorine to cope with the increased demand.

The outflow into Lake Michigan of some 500 cu.ft./sec., or more, from the Indiana Harbor Ship Canal is even more important than the American Maize effluent, and the danger of this pollution will be greatly minimized now by reason of the separation and treatment of sanitary sewage, installation of oil separators, and recovery of organic solids by the various industries. The flow of the river toward Illinois will also be improved and much of the B.O.D. load will be eliminated.

This expenditure of $12,000,000 is one of the most noteworthy steps taken by industry in many years, to abate long-standing pollution, and it indicates the magnitude of one of these regional problems.

Buffalo-Niagara Frontier. The situation downstream from Buffalo, in the Niagara River, has drawn the attention of state, national and international authorities, largely because of the same difficulties as those noted in the Calumet Region. The dilution by the flow of the Niagara River, some 200,000 cu.ft./sec., is far greater than needed for oxygen balance, but presence of phenol, other taste-producing substances, or interference with chlorination are the difficulties cited by the authorities for abatement of waste discharge. Many industries are located along the Niagara or Buffalo Rivers, and some degree of B.O.D. reduction, plus removal of phenol, cyanide or other vaguely defined chemicals is demanded by the International Joint Commission.

As in the Calumet case, expenditures are listed as the major indications of waste abatement by industry, and dilution of wastes by circulated lake water is also hoped for as a means of reducing the concentration of chlorine-consuming wastes.

TABLE 2.—EXPENDITURES ON WASTE ABATEMENT, CALUMET INDUSTRIES

Company	Expenditures to 1949
Cities Service	$1,500,000
Socony-Vacuum	136,000
Sinclair	550,000
Standard Oil of Indiana	3,500,000
Youngstown	650,000
Inland	2,185,000
Carnegie-Illinois	2,000,000
National Tube	155,000
American Maize	727,000
Cudahy	297,000
Carbide and Carbon	282,000
Du Pont	192,000
Total	$12,114,000

Here is a case where problems have arisen even though the dilution is so great as to obviate all the usual visual evidences of pollution. However, bacterial pollution of water supplies is considered to be 500 times as sensitive as pollution which destroys oxygen, and thus even these well-situated industrial plants are not free from criticism.

Conclusions

Location of industries should be decided upon after careful consideration of the consequences of discharge of wastes into the nearest stream, lake or harbor. The resulting pollution may require abatement for a number of reasons, viz.:

1. It may deplete the dissolved oxygen to:
   a. Zero, with anaerobic conditions and consequent odors, death of fish, and general nuisance.
   b. Insufficient amount to support fish life, i.e., less than 4.0 p.p.m.
2. It may contain organic matter which will interfere with proper use of chlorine in water purification.
3. It may introduce toxic chemicals which will kill fish and suppress normal biological life.
4. It may render the receiving water unfit chemically for downstream use.
5. It may make streams acid or cover their surface with oil or scum.

Other local conditions may be considered as proof of pollution, and frequently established industries have to face criticism for other reasons, sometimes not well supported by hard thinking or ethical balance of advantages to be gained in relation to money expended for waste abatement.

Experiences with various types of industries and contacts with many waste problems have been described, to show the variety of problems encountered, and the methods by which the problems have been alleviated. The degree or type of treatment varies in almost all cases, unless wastes are highly diluted in admixture with sewage, and normal biological sewage treatment methods can be used. This is the situation desired by most industries, but care must be taken that the sewage is considerably in excess, otherwise the complications may be even worse than if no sewage were present.

When new industries are to be established, or old industries encounter pollution problems, the best course is for the industrial concern to learn all it can, by its own efforts, concerning its wastes and the best method of treatment. Then it can decide how far it is justified to go in order to meet city, state, United States or international demands for waste abatement and can better appreciate the justice of these demands as opposed to the responsibility of spending

stockholders' money for waste treatment.

The problem is complex and not one that can be solved solely by engineers, chemists or biologists working alone. Only by use of all these sciences, and by weighted consideration of the relative contribution by each science toward a coordinated result, can the problem be properly solved.

Discussion

Anonymous: I would like to emphasize, from the industrialists' viewpoint, that waste disposal is becoming more and more important; in fact, I know of instances where waste disposal considerations were really the primary consideration in a decision between two plant sites.

I would like to emphasize another point, and that is, in all cases a pollution problem is an individual one. Rarely is it that you can consider it in the light of what has gone before, simply because your situations are never identical; hence you can't work out a waste problem solution on paper and apply it to another situation, for you still have to take into consideration your receiving waters.

Dr. Mohlman's views on the use of a stream for purification purposes of a waste unfortunately are not held in general. I wish that they were. It isn't that we would like to have all the stream clarification done for us, but in too many instances we are expected to treat a waste as if it were going into a drinking water supply, and that is not always the case; that last 20 per cent pollution is sometimes a great deal more expensive to remove than the first 80 per cent, and in some cases it can amount to several times the original cost.

Time was when you would go out and build a plant, and you put in either a septic tank or your sanitary wastes were mixed with industrial wastes. Well, a septic tank is an easily built thing and it is easily forgotten. That is one trouble with it. It is not held in any great favor in this day and age. Usually control agencies require at least primary treatment and in some cases the equivalent of secondary treatment. It has simply become, along with a lot of other things, part of the cost of doing business; you have to treat your sanitary sewage adequately these days.

Anonymous: What is the possible maximum oil waste from an oil refinery that can be tolerated in the discharge to a sanitary sewage disposal plant, where biological action is being used for taking care of sewage?

F. W. Mohlman: That has caused some trouble at different places, due to unknown amounts. However, if you have an A.P.I. clarifier and you keep that effluent below 25 or 30 p.p.m., I don't think that would cause trouble in a biological plant. But I don't believe you could discharge it without some effort to remove the oil from such an effluent. On the other hand, I have my doubts that you could maintain that at 15 p.p.m. continuously. Of course, it depends on the particular problem, and I wouldn't want to answer it generally. But I would say that would be a pretty safe way of solving the problem.

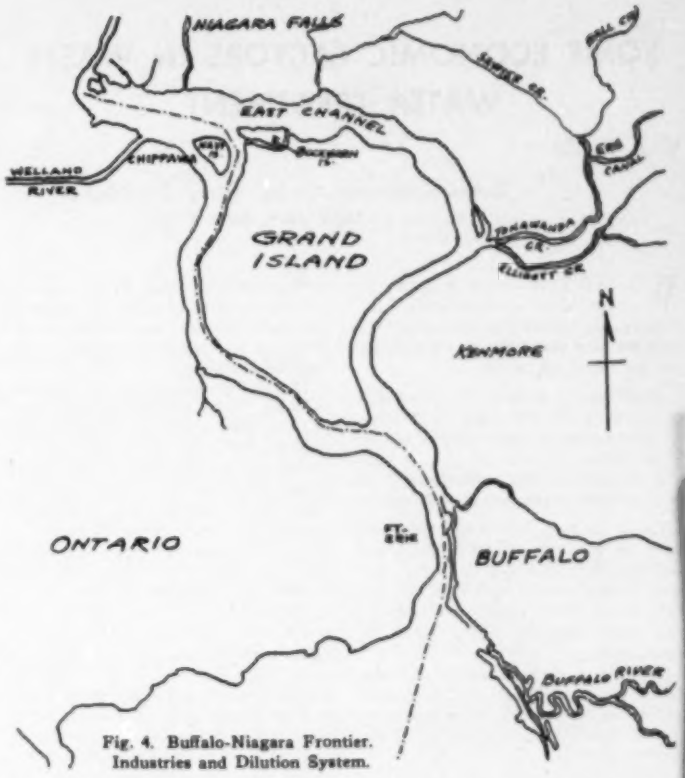

Fig. 4. Buffalo-Niagara Frontier. Industries and Dilution System.

Anonymous: Is there any preference between activated sludge treatment and high rate trickling filters for antibiotic wastes?

F. W. Mohlman: Frankly, I haven't had experience with activated sludge treatment of antibiotic wastes. Possibly it might work. But I prefer aeration plus a high-rate or low-rate filter. I doubt whether straight activated sludge would work, as there are toxic properties there that are rather hard on activated sludge treatment.

W. W. Hodge (Mellon Institute, Pittsburgh, Pa.): On an inspection trip in April, 1948, to the Southwest Sewage Treatment Works, Sanitary District of Chicago, Ill., I believe we were told that the plant was treating more than 300 million gal. of liquid wastes/day, and that the industrial wastes load was about equivalent to the load of domestic sewage. Would you tell us about the industrial wastes that are successfully treated by the activated sludge process at the Southwest Works.

F. W. Mohlman: All the packing-house wastes, with equivalent population of a million, are treated in this plant. But the plant treats, we will say, 400 million gal. of sewage/day, of which only 50 million is packing-house wastes. Of course, there are other wastes present but the packing houses are by far the large factor, and their wastes are treated successfully only by reason of the high dilution. We notice a great difference between the Sunday and week-day conditions.

However, at Sioux Falls an equal load of sewage and packing-house wastes is treated by various processes, filters, activated sludge, preliminary sedimentation. When you have this higher concentration you must use multistage treatment. But we have enough dilution that we are able to get a satisfactory effluent with all the Chicago packing-house wastes.

SOME ECONOMIC FACTORS IN WASTE WATER TREATMENT

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WATER is the major raw material employed by most industries and utilities. Consequently two important problems are presented in manufacturing and utility operations:

1. Obtaining a low cost, abundant supply of water which is satisfactory for various plant requirements.
2. Disposing of contaminated or polluted waste waters after use.

Usual methods of water treatment such as coagulation, flocculation and sedimentation, lime soda or zeolite softening and filtration have been successfully employed in making all kinds of raw water supplies useful for plant operations.

This paper covers some of the economic factors entering into the selection and operation of waste water treatment installations in certain industries. These applications are:

a. Treatment of acid and plating wastes
b. Treatment of white waters from pulp and paper mills
c. Treatment of oil-bearing wastes from petroleum refineries and manufacturing plants

In some plants, proper treatment of waste waters can help solve the problem of insufficient or high cost raw water by providing a supply of clarified waste water of proper chemical composition. This is of value where normal surface water supplies are insufficient, where they are highly polluted and costly to purify, and where the underground water table is low.

Restriction on Disposal of Waste Waters. Most states have adopted regulations prohibiting the introduction of acid or alkaline wastes into rivers and streams. Neutralization of such waste waters is therefore required.

Such waste waters often contain other objectionable impurities such as toxic metallic cations, which must also be reduced to safe low values by pretreatment. Similarly, in most towns, highly acid plating or other wastes cannot be introduced into sewer mains without neutralization. This is done to prevent corrosion of pipe and fittings in the sewer lines and also to prevent upsetting of the treatment processes in the main sewage plant.

The seriousness of stream pollution by waste waters containing large quantities of pulp and paper stock, mainly cellulosic in nature, is apparent to all the pulp and paper mill owners. Work is being done by this industry and various trade groups so as to conform to regulations of state sanitation boards. In contrast to many industries where usable materials cannot be recovered from wastes, the treatment of white waters can be profitable by recovering pulp and paper stock. State regulations now require reduction of solids in pulp and paper mill waste waters to values low enough to avoid increasing the pollution load on streams and surface supplies. In many cases this means a permissible suspended solids or stock concentration of less than 0.25 lb./M gal. in the waste water discharged.

Suspended solids and oils from petroleum refineries and other plants present problems of pollution similar to those from pulp and paper mills. These organic products increase the B.O.D. of surface supplies and create problems of sanitation and purification for municipalities and industries drawing raw water from the same streams. Consequently, state regulation agencies have prescribed limits on concentration of such impurities in waste waters discharged into surface supplies. In some cases, a limit of 3 p.p.m. of oil in waste waters discharged into open streams has been required by state boards, and limits on such materials as phenols and allied products which present serious taste and odor problems also have been prescribed.

Sewerage boards in some large cities have refused to permit discharge of waste waters containing oils and organic suspended solids without pretreatment. More regulations limiting impurities which can be tolerated in open streams and local sewerage systems are being established, and the assistance of the Federal government is now available to help solve problems presented by the waste waters of industry.

Factors in Design and Cost of Waste Water Treatment Equipment. There are many waste problems that require laboratory research and pilot plant investigations before the treatment process and the equipment design are established. However, there are also many problems and applications where the pattern of waste water composition, chemical treatment, and equipment design is well established on the basis of experience and operating data with existing installations.

Selection of the proper process and equipment for treating any waste water is mainly a problem in economics. It is the job of the engineer to select the process, the chemical dosage, and to design the equipment which will yield the required treated waste water at lowest cost and with greatest convenience to the existing plant flow sheet.

Aside from the design and proper performance requirements, it is usually important to reduce the long-term operating cost of waste water treatment plants to the lowest values. Factors which enter into long-term operating costs are:

a. Cost of chemicals required for treatment
b. Initial investment required for installed equipment
c. Cost of labor for operation of equipment
d. Maintenance of equipment parts
e. Possibility of recovering valuable products or reusable water from waste water

Treatment of Acid and Plating Wastes

The small plating plant, using copper, cadmium and chromium plating, is frequently faced with the disposal of small volumes of these wastes to existing sewer lines. In most cases, the flow of acid-plating wastes is continuous during plating operations and the amount of acid and metallic impurities is fairly constant in value.

For such requirements, a simple alkali feeding system is shown in Figure 1. If necessary, hypochlorite may be added also. The system is for constant rate operation with push-button semi-automatic control. When the plating line is in operation, a constant stream of acid waste containing small quantities of metallic cationic impurities flows to a short detention, baffled mixing chamber into which lime and hypochlorite are fed in preset quantities. Lime, fed by means of a simple dry feed, is diluted with plant water in a pump suction box and pumped with a centrifugal pump through easily cleaned rubber hose into the baffled mixing tank. Hypochlorite is fed for oxidation of traces of cyanide

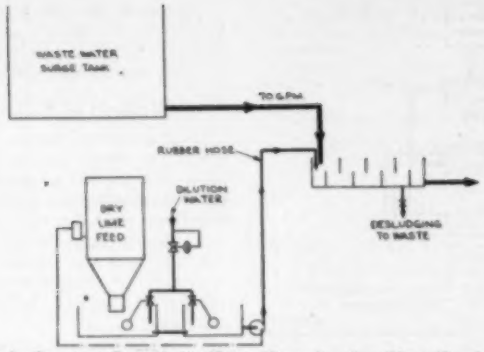

Fig. 1. Simple Constant Rate Acid Waste Neutralization Plant Employing Lime.

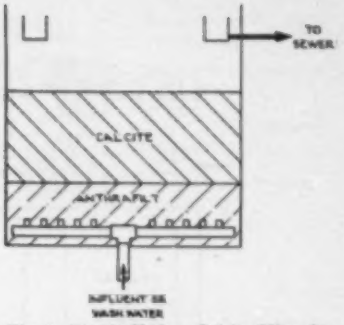

Fig. 2. Simple Upflow Calcite Filter for Small Volume Acid Waste Neutralization.

and other organic impurities. Chlorinators are used where larger quantities of chlorine are required. This equipment usually costs $1500 to $2500 installed depending on size of feeders, quantities of impurities and other factors and is easily installed and convenient to operate. In some locations caustic soda is inexpensive and easily available and is employed in place of lime.

Figure 2 shows a simple upflow calcite filter unit which can be employed to neutralize small concentrations of presettled acid wastes. Calcite ($CaCO_3$) is a low cost chemical (average cost 2 cents/lb.) and can be easily replaced in the open-top upflow filter unit. Upflow rates as high as 3 gal./(min.)(sq.ft.) can be employed for certain applications. Chlorination of the waste water also may be used where necessary. The filter shell is usually lined with a corrosion-resistant material and corrosion-resistant alloys are used for piping and fitting construction. A simple, open-top upflowing, lined-steel filter unit of design shown in Figure 2 would cost $750 to $1400 depending upon flow rate of 50 to 150 gal./min.

In some plants, large volumes of acid waste waters of varying acid content require neutralization before discharge into settling basins and open streams. In such cases it is necessary to vary the lime dosage in proportion to acid content. It is also important, for lowest operating cost, to employ minimum doses of lime.

Figure 3 shows a typical arrangement employed for such applications. With this system the acid wastes are pumped at a constant rate into the baffled mixing trough and lime is fed through a pH meter-controlled orifice valve which proportions lime in relation to pH of the mixture. Where necessary, chlorine can be fed from a vacuum chlorinator in order to reduce operating cost. With this system, stoichiometric quantities of lime are fed and operating cost for lime is approximately 0.17 cents/M gal. for each grain/gallon of acid in the waste water. Equipment shown in Figure 3 for treating 250 gal./min. of acid waste water containing an average of 20 gr./gal. of free mineral acids would cost $2500 to $5000 depending on concentration of acids and total volume of waste water.

Some plants having acid wastes have been able to utilize alkaline wastes from adjacent plants as an inexpensive neutralizing agent. In such cases, a simple arrangement involves presettling and retention, followed by metered and controlled pumping of acid and alkaline wastes in proper proportions for neutralization.

In other cases, high concentrations of objectionable impurities such as oil, chromium, zinc, and cyanide salts are present in waste waters and must be reduced to satisfactory low concentrations by proper treatment. In such cases, an arrangement as shown in Figure 4 (*4*) is employed, utilizing primary and secondary clarifying units. The secondary clarifying unit can be a Solids-Contact Clarifier of the type shown in Figure 5. (*1*) A coagulant such as ferrous sulfate, lime or soda ash and a coagulant aid such as activated silica are used for this purpose.

Various methods have been suggested for recovering chromium, copper, and zinc from brass mill wastes by means of ion exchange but, at the present time, practical means for recovery have not been completely successful.

Treatment of White Waters from Pulp and Paper Mills

The amount of stock comprising both fiber and filler which is discharged and lost in waste waters from pulp and paper mills is high. In Table 1 (*2*) the concentrations of stock in white and waste waters from four mills are shown. In some large paper mills, as much as 6 tons and as high as 50 tons of stock, dry basis, are lost each day.

TABLE 1.—STOCK CONCENTRATIONS IN WHITE WATER

Mill	Amount of White Water Discharged gal./min.	Range of Solids Concentration lb./M gal.	Amount of Stock (Fiber and Filler) Lost lb./hr.	Range of pH of White Water
A	400	3–4.5	90	8.5–6.5
B	1400	4–12	500	9.8–6.5
C	2000	2–4	360	8.5–7.0
D	1200	3–6	290	4–7

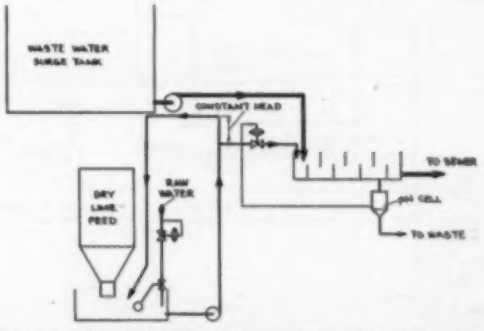

Fig. 3. Proportionating Acid Waste Neutralization Plant Employing Lime.

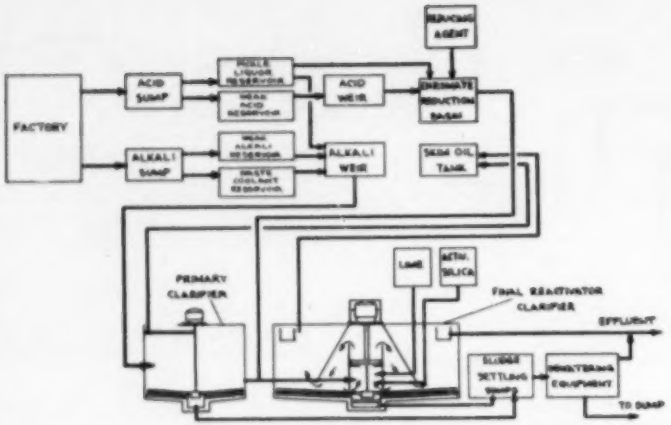

Fig. 4. Metal Plating Waste Treatment Plant.

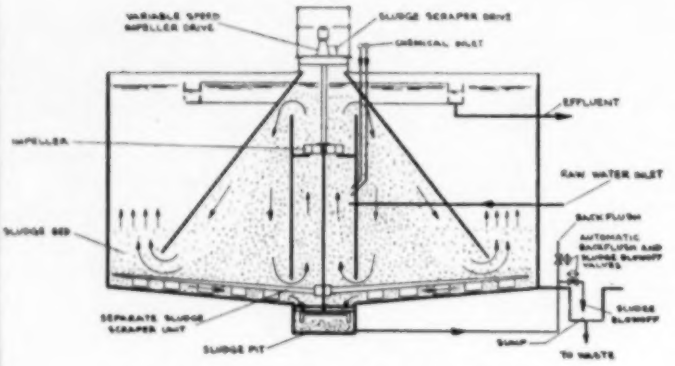

Fig. 5. Graver Reactivator (Solids Contact Unit).

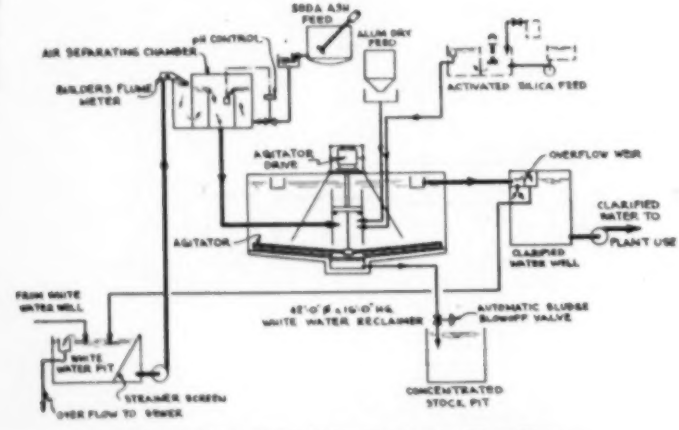

Fig. 6. Typical White Water Reactivator Flow Sheet.

The reason for this loss lies in the inability of the savealls and other machines to effect a complete separation of solids suspended in water.

Methods of Treatment

There are many devices for treating white and waste waters from paper mills. Savealls can be classified by the methods employed in separating fibers and fillers from the water as follows:

1. Screen filtration without pretreatment
2. Settling in long retention basins with or without chemical pretreatment
3. Pretreatment with chemicals and pressure aeration followed by flocculation and skimming
4. Coagulation with chemicals and clarification in a Solids Contact reclaimer

This section will cover design, performance and operating costs obtained with Solids Contact reclaimers (Item four, above).

With Savealls listed under items 1 to 3 above, the separation of the fibrous solids is accomplished mechanically either by retaining the fiber on fine mesh wire screen, by using large tanks so that the velocity of flow is so small that the fibers settle by gravity, or by adding reagents which float the fibers to the top. Once the fiber or stock is separated, with these devices, it is withdrawn from the scene of action and no longer plays any part in the treatment of the waste water.

Although the quality of effluent obtained with savealls may be satisfactory for some reuse applications, it is not satisfactory for many cases, particularly, where the clarified waste water is employed in spray nozzles of Broughton showers. For many such applications, concentrations of stock of less than 0.25 lb./M gal. are required in the clarified waste water. Such low concentrations are easily obtained in Solids Contact reclaimers.

Solids Contact Reclaimer. Solids Contact reclaimers make use of a principle employed successfully in the chemical treatment of water supplies—a prolonged contact of the incoming waste water and chemicals with a large concentration of previously accumulated suspended solids. Intimate contact with the suspended solids provides vast adsorptive surface areas to which the coagulated stock particles can adhere. More effective and more complete coagulation is effected with an increase of average size and weight of the stock particles which settle out more rapidly. By providing proper contact with solids, more than 95% of incoming waste water solids is removed in a minimum of time and space.

Figure 6 shows a diagrammatic sketch of a Reactivator-type Solids Contact

reclaimer and a flow sheet illustrating a typical plant installation. As shown in Figure 6 an agitator pump is provided in the central uptake of the reclaimer, which mixes water, chemicals, and recirculated solids. Accumulated solids are recirculated by means of the agitator pump at two to six times the rate of flow of influent and effluent. The mixture of water, chemicals and solids leaves the uptake and enters a conical flocculation zone where particles coalesce and chemical reactions are completed. At the bottom of the conical section, the mixture is made to flow upward to the collector through a settling section of increasing upward area. The vertical velocity is thereby decreased. The heavy, large particles settle out on the bottom of the Reactivator and are continuously moved to a center sludge pit by slowly rotating sludge scraper blades. Lighter solids separate from the effluent water stream at the bottom of the conical section and are recirculated through the central uptake by the agitator pump.

The main features of a Solids Contact reclaimer of this type are:

1. A prolonged contact of accumulated solids with coagulation chemicals and incoming water
2. Recirculation of previously formed solids at high rates
3. Positive movement of settled solids to a concentrated sludge pit
4. A large settling area (virtually the full bottom of the Reactivator) for accumulating settled solids

Coagulating chemicals, where necessary, are fed into the Reactivator by a proportionating pump or a wet-type proportionating feed of the type shown in Figure 7. The wet-type proportionating feeder consists of an inclined drawoff pipe, the top head of which is suspended by a chain wound around the feeding sprocket of the chemical feeding device. A totally enclosed, motor-operated gear reduction unit of special design causes the sprocket to rotate. During operation of the feed, the chemical tank is filled with the chemical solution or suspension and the feeding sprocket rotates, slowly lowering the chain and the end of the drawoff pipe below the liquid level, thus feeding chemical solution down the swing pipe at a controllable rate. An inlet flow meter is usually employed to actuate the device through a contactor and timer arrangement. Feeding rates can be quickly and easily adjusted by remote control.

Although treatment chemicals are required in many cases, there are applications where sufficient alum and other coagulants are present in the waste water itself in sufficient quantities. This simplifies plant operation and reduces operating cost.

Economics of Treatment. As an example of over-all cost for treatment of white water by Solids Contact reclaimers, consider a typical paper mill where the following conditions are found:

Maximum amount of white water discharged to waste	2,000,000 gal./day
Average amount of stock in white water	2.5 lb./M gal.
Average temperature of wasted white water	85° F. summer
	70° F. winter
Maximum amount of treated well water required	2,000,000 gal./day
Actual cost of treated well water	2 cents/M gal.
Average temperature of well water	55° F.
Value of stock in white water, average	$35/ton

It is desired to install a Solids Contact reclaimer to clarify the white water, so that most of the treated water can be reused in the plant, and to recover as much stock as possible.

Figure 6 shows a flow sheet for this installation. The treated effluent from the reclaimer contains 0.25 lb./M gal. of stock.

(A) Recovered Products

The stock recovered from this plant is: 2.5 -0.25 = 2.25 lb./M gal. or 2.25 tons/day. With the stock concentrated to 3% in the sludge pit then

$$\frac{4{,}500 \text{ lb./day}}{0.03} = 150{,}000 \text{ lb. or } 20{,}000 \text{ gal.}$$

(B) Recovered Water

Recovered waste water = 2,000,000 − 20,000 = 1,980,000
Blowdown of treated white water discharged to waste to maintain total dissolved solids in recirculated water below 2500 p.p.m. = 25% or 400,000 gal./day
Recovered clarifier white water for reuse: 1,980,000 − 400,000 = 1,580,000 gal./day

(C) Recovered B.t.u.'s

1,580,000 gal./day water average recovered

$$\text{B.t.u.'s} = \left(\frac{85 + 10}{2}\right) - 50 = 22.5° \text{ B.t.u./lb. or } 300{,}000{,}000 \text{ B.t.u.'s/day}$$

Costs

(A) Cost of Equipment

1400 gal./min. Reactivator as per flow diagram Figure 6; dimension: 40 ft. × 15 ft. straight. 5/16-in. steel shell on concrete pad bottom; complete with internal uptake, conical sections, controls, and accessories including:

1—Wet alkali proportionating feed with pH control
1—Alum dry feed
1—Activated silica feed
1—Air separation tank

Concentrated stock automatic blowoff equipment—	
Approximate equipment cost	$45,000
Approximate cost of erection and installation, including foundations, etc.	$35,000
Approximate total cost	$80,000
Amortized equipment cost (10 years)	$ 8,000/year

(B) Chemical Operating Cost

Soda Ash = 0.3 lb./M gal. or 600 lb./day @ 1.6 cents/lb. = $10.00/day or	$3000/year
Alum = 400 lb./day or $3.50/day or	$1000/year
Total chemical operating costs	$ 4,000

(C) Cost of Labor

Cost of labor to operate plant	$8,000/year
Total costs per year	$20,000

Savings per Year Due to Reclaimer Installation

a. *Recovered stock*—2.25 tons/day—50% used or 1.13 tons/day valued at $35/ton = $39/day	$11,700/year
b. *Recovered water*—1,580 M gal. @ 2 cents/M gal. = $32.00/day or	$ 9,600/year
c. *Recovered heat*—300,000,000 B.t.u.'s/day @ average cost 20 cents/1,000,000 B.t.u.'s = $60/day or	$18,000/year
Total value of recovered products	$39,300/year
	− 20,000
Savings per year	$19,300

This calculation indicates that the savings would permit payment of initial investment in about four years and thenceforth would permit savings of approximately $19,300/year under stated price conditions. In addition, pollution of surface supplies is eliminated. Any concentrated stock not reused in the plant can be burned to avoid lagooning. Treated waste water can be discharged

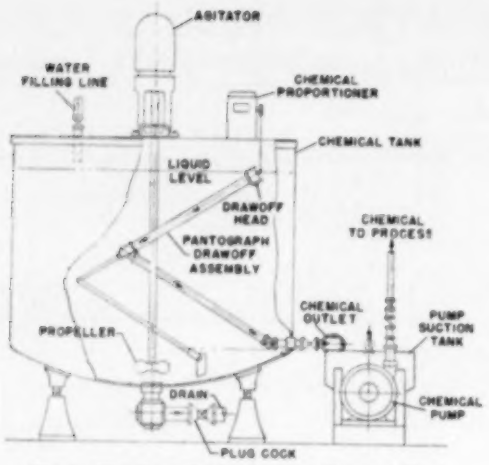

Fig. 7. Wet-Type Proportionating Chemical Feed.

to waste without danger of pollution because it contains less than 0.25 lb./M gal. of stock.

A 100 gal./min. Solids Contact Reactivator unit of similar design would cost approximately $22,000 installed. The cost of machines for intermediate flows would be roughly proportional to values given above.

Simplified Solids Contact Reclaimer. Figure 8 shows a cross-sectional sketch and flow diagram of a simplified Solids Contact reclaimer which can be employed for smaller plants where nature of the solids is such that agitation, recirculation of solids and positive sludge scraper solids removal is not necessary.

As shown in Figure 8 there are no internal moving parts in this machine. Incoming white or waste water merely flows over an air separator baffle and mixes with chemical, if required, in a long, high velocity downtake. The bottom edge of the downtake is designed so that it projects about 70% of the way into the bottom cone. Accumulated solids are suspended by the upflowing water to provide a deep bed of sludge through which waste water and chemicals must pass to flow to the outlet collector. Low upward settling velocities are employed, surrounding the downtake in this unit and this, together with the lower viscosity of warm water, assures maximum settling of coagulated solids. The bed of sludge is maintained at a low point in the unit and a deep section of widest area is provided above the sludge bed to obtain optimum results. Accumulated solids settle down into the bottom of the cone and are blown off to waste, automatically.

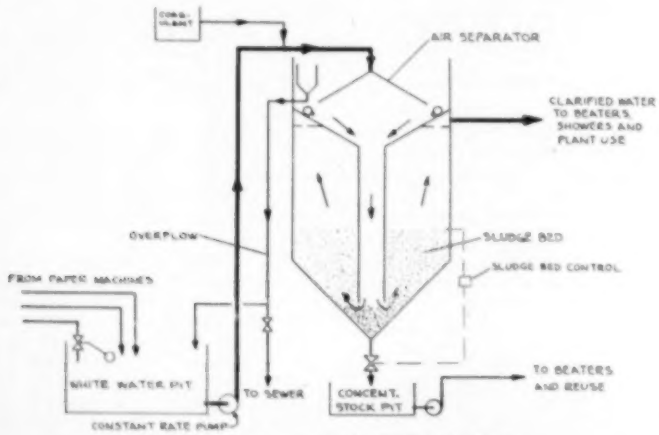

Fig. 8. Simple Graver White Water Reclaimer.

Treatment of Oily Waste Waters

In many regions of the country, the discharge of waste waters containing oil and petroleum products has been a serious source of pollution of surface water supplies. In addition to pollution, in arid areas, obtaining a sufficient quantity of water for cooling and other petroleum refinery purposes, is a serious problem.

The treatment and clarification of oil containing waste waters, therefore, helps to avoid stream or surface pollution, and to obtaining sufficient water for plant purposes.

Figure 9 shows a flow diagram of existing Reactivator installations and other equipment in successful operation at a Southwest refinery (*3*). Originally approximately 1500 gal./min. of oil containing waste water was discharged into a small stream. As a result of the installation and operation of the equipment, approximately 300 gal./min. of clarified water is discharged to waste and 1200 gal./min. are reused in the refining proper after treatment to soften and remove oil.

Table 2 shows the influent waste water and effluent composition at this plant.

Table 3 shows the volume of water treated in each Reactivator unit.

Concentrated oily sludge obtained from the Reactivators is burned to avoid lagooning.

This plant costs approximately $125,000 installed.

Chemical operating costs average 4.3 cents/M gal.

Savings obtained by reusing clarified water average more than several dollars per day. In addition a continuous supply of water is assured without reliance on a droughty stream and, of course, the problem of pollution of this stream by oily wastes is eliminated.

Figure 10 shows a photograph of a large 1200 gal./min. Reactivator located at this plant.

For some applications, much smaller quantities of oil require removal from water. In such cases, preformed floc oil-removal filters can be employed. Figure 11 shows a photo of an existing 1000 gal./min. preformed floc oil-removal filter installation at a California public utility. Oil concentrations in costly condensate up to about 50 p.p.m. are treated with small quantities of alum in precipitated form as $Al(OH)_3$ and the mixture made to flow through Anthrafilt oil-removal filters containing rotary surface washers. These filters are first coated with a layer of $Al(OH)_3$ immediately after backwashing and a continuous feed of $Al(OH)_3$

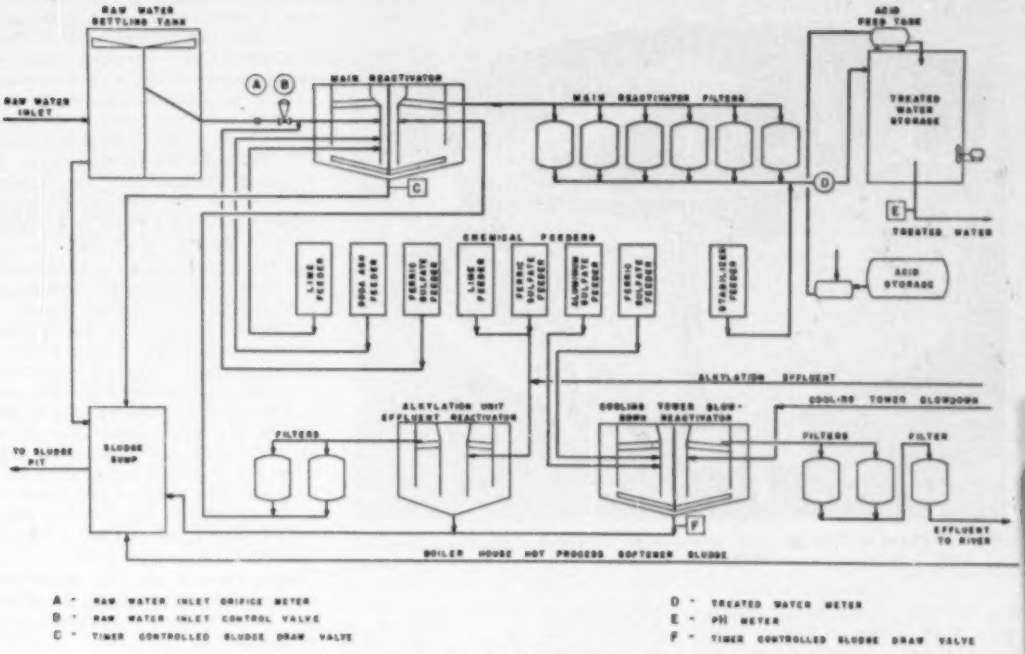

Fig. 9. Flow Sheet of Graver Refinery Waste Water Installation in Southwestern Refinery.

with the oil assures a continuous adsorptive layer for removing the oil.

The initial investment for such open-air filter installations is not high and, of course, the chemical operating cost is quite low, usually less than 1 cent/M gal. In addition, labor costs are low because of minimum maintenance required with foolproof design. In the case of the installation shown in Figure 11, automatic filter backwashing and precoating and operation are obtained to minimize labor costs even further. It has been estimated that savings on recovered condensate at this point average more than $1/M gal.

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2. Calise, V. J., *Paper Trade J.* (Aug. 12, 1948).
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Discussion

Anonymous: Can a precipitate that is being formed, be removed in this system of baffling? For example, if you are running sulfuric acid effluent into this baffle type of mixing with your neutralizing agent—would that system suffice, would you not get settling in that baffling system and need some positive means of agitation to remove the precipitate?

V. J. Calise: I believe you refer to the simple lime neutralization system. There would be some settling but the unit can be designed so that precipitated material can easily be removed by proper desludging with a sludge spider or cone. In other words, we do not necessarily require any agitation other

TABLE 2.—ANALYSES OF TYPICAL WATERS*

	River Water	Raw Water from Settling Tank	Treated Water	Net Effluent
Dissolved solids	2,810	3,240	2,490	11,300
Total hardness	500	357	128	513
Calcium hardness	410	280	69	320
Magnesium hardness	90	77	59	192
Phenolphthalein alkalinity	0	68	65	...
Methyl-orange alkalinity	154	225	159	.....
Chlorides	1,145	1,400	1,400	5,020
Oil	0	250	20	Nil
Sulfates	.....	.....	.....	2,660
Ammonia ion	.....	.....	.....	313
Cresols	.....	.....	.....	Nil

* All figures are given in parts per million.

TABLE 3.—DETAILS ON TREATING SYSTEMS

System:	Main	Cooling-tower blowdown	Alkylation-unit effluent
Maximum rate (gal. per min.):	1300	140	20
Water source:	Trap and river water	Cooling-tower blowdown	Alkylation-unit lime pit
Purpose:	Softening	Clarification and sulfide removal	Neutralization and fluoride removal
Chemicals used:	Lime Soda ash Ferric sulfate	Ferric sulfate Aluminum sulfate	Lime Ferric sulfate
Treater size (diameter of reactivator):	45 ft., 0 in.	13 ft., 6 in.	7 ft., 4 in.
Filters containing anthracite (number and diameter):	Six, 10-ft., 6-in.	Two, 5-ft., 6-in.	Two, 3-ft., 6-in.
Disposal of water:	To treated-water storage tank; to cooling towers as make-up	To river	To main treating system

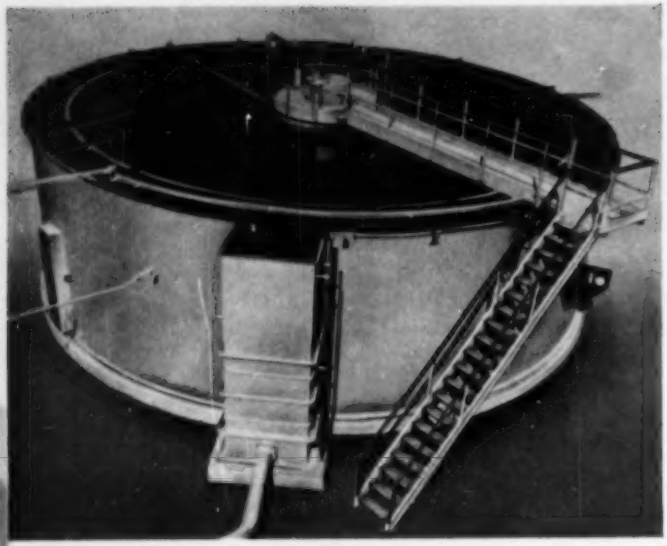

Fig. 10. Photo of 1200 gal./min. Waste Water Reactivator Clarifying Unit at Southwestern Refinery.

than the flow of water and a sludge spider in the bottom, or perhaps a baffling arrangement which will permit you to locate the precipitate in a conical unit section in which sludge accumulates and can be "blown off" to waste.

Anonymous: We have heard about the treatment of acid waste as a simple problem. The treatment of mine acid is not a simple problem. It is a local problem which applies to certain states in the East, not so much in the West. The general estimate in western Pennsylvania alone is that there is better than a million tons of sulfuric acid produced a year and fed into the streams. Along with that there is sufficient iron to operate two 600-ton blast furnaces, which is a considerable amount of sludge. The molecular weight of sulfuric acid is 98, carbonate is 100. So we can figure pound for pound, calcium carbonate or limestone required is better than a million tons a year in the case of western Pennsylvania alone to treat that acid. That is speaking from the pounds, disregarding the material costs.

When we talk economics, we have on top of that the possibility of collecting the acid into a suitable treatment plant, a fluctuation of flow between seasons at a ratio of about 10 to 1, and we have plants where they will deliver a few hundred gallons a day up to a million gallons a day for a given plant.

It has been brought out many times that there is no method of treatment of mine acid in western Pennsylvania. I simply want to mention a few of these points, to indicate that it is not a simple matter, that it is not an economical treatment as we consider costs. The cost of lime alone is anywhere from a half cent to two cents a pound, and if we figure two cents a pound a million tons a year will be 40 million dollars. I don't think any of us feel that is an economic solution in western Pennsylvania, and I don't think we feel that the treatment of mine acid is a simple problem.

Anonymous: Is this Anthrafilt system for removing oil condensate a fixed bed with a backwash, or is it a continuously moving bed?

V. J. Calise: The preformed floc oil-removal filter comprises a fixed granular bed of Anthrafilt, usually two or three feet deep, which has at the top of the Anthrafilt bed a particle size of about 4/10 mm. A thin layer of precipitated alumina is formed on top of this bed and that layer on top of the bed helps to break up the oily emulsion in the condensate. In addition to the precoat of preformed floc on top of the bed you also continuously feed about one to three p.p.m. of precipitated alumina or iron hydroxide into the condensate as it enters the filters, and the combination of the continuous feed plus the precoat on top of the filter bed breaks the oil emulsion and filters it out.

Anonymous: Then you have the problem of cleaning the bed periodically?

V. J. Calise: That is right. When the pressure loss rises to about two to four pounds you have to clean the bed. The way to do that, of course, is to use a backwash rate which permits washing out all the accumulated materials. In addition, we use, in some cases, rotary surface washers, which are high velocity jets of water; these break up the mat formed on top of the bed and assist in washing out the precipitated or coagulated oil.

Anonymous: And is the condensate you recover there suitable for boiler feed?

V. J. Calise: Yes, it is.

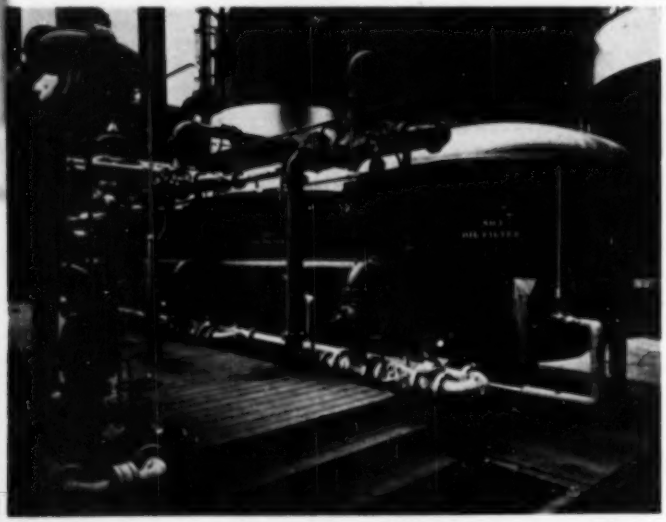

Fig. 11. Graver Preformed Floc Oil-Removal Plant Treating 1000 gal./min. of Oily Condensate at a West Coast Utility.

TREATING TANK-CAR WASTES

GREGOIRE GUTZEIT

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TANK-CAR cleaning operations produce wash waters which are unusually complex, and, moreover, highly variable in their composition, their concentration and their flow. This particular character of the waste requires purification methods which involve flexible design of the treatment installation.

Of course, the process should be adapted both to geographical circumstances and to existing state or federal laws. For instance, in areas where the effluent of the works can be discharged into a large stream, supplying a high dilution factor and good self-purification, the degree of treatment does not have to be as complete as in the case of a small clean river receiving the final discharge. In desertic localities, simple lagooning is permissible. In agricultural sections, certain types of pollution are specifically objectionable (e.g., alkalies in citrus country), while others may be deemed allowable. The existence of a municipal sewage installation is another favorable circumstance, as it makes possible the design of a compact and relatively low-cost chemical system, leaving final purification to the digesters and biological filters.

While a simplified installation for the treatment of wash waters from selected tank cars has been formerly described (*5*), the present paper deals with the method developed for a new General American repair and maintenace plant which, as a result of local conditions, involves a solution of the purification problem in its broadest scope.

This new shop will be located southeast of the Borough of Saegertown, Crawford County, Pa. The waste, after treatment, will be discharged into "French Creek" through an existing sewer line. No municipal sewage works exist presently in Saegertown.

Tank-Car Cleaning. The technique of tank-car cleaning (*4*), an indispensable first step for traffic requirements and repair work, is a standardized and simple operation, except in some special cases. It depends obviously on the last commodity shipped, but generally involves draining, steaming or/and rinsing with water.

Steaming can be carried out with or without an additional reagent or solvent. In the former case, a so-called "syphon" is used, i.e., a *T* attachment, which serves the purpose of atomizing water, kerosene, a detergent or caustic soda into the steam jet.

Kerosene is used for cleaning heavy petroleum products. Caustic soda solution is injected to saponify vegetable oils, animal greases and similar glycerides. Wet steam is applied to acid and alkali tanks. Detergent solutions are helpful with commodities such as rosin, tar oils, etc. (*4*).

Liquids resulting from drainage mixed with the wash waters and steam condensate represent the fluid waste of these maintenance plants.

There is also produced some solid waste, such as asphalt, creosote, sand, clay slurry, etc., which is relatively easy to handle. When the material is combustible, an incinerator is the simplest means of disposal. Incombustible inorganic matter can be dumped, or used as fillage, surfacing, etc.

In order to make possible an efficient treatment of the wastes, the tank cars are segregated into the following five groups according to the last commodity shipped:

Cars having been last loaded with clay, Fuller's earth, stearic acid, creosote, etc., are cleaned on a separate rack. Solid insoluble and incombustible materials are dumped. Organic products having a low-melting point are liquefied by heat, drained and incinerated. The residue is removed by mechanical means and finally by steaming.

Special pressure tanks loaded with liquefied gases (boiling point below ordinary temperature) such as oxygen, carbon dioxide, butane, chlorine, etc. (*4*) do not present any stream pollution problem, as these products will volatilize when the pressure is released. If washing is necessary, they are cleaned on the Solubles rack.

Cars having been last loaded with soluble compounds, for instance, inorganic and short chain organic acids, ethyl and methyl alcohol, glucose, molasses, sodium silicate, wine, etc., are washed generally with clear water, sometimes both washed and steamed. In the case of volatile liquids, a large part will escape in the form of vapors when steam is applied.

Cars having been used for the shipment of insoluble commodities, such as vegetable or animal oils, petroleum products including gasoline, naval stores, coal tar oils, organic chemicals (ketones, aldehydes, etc.) are cleaned over a separate flume either by steaming alone, by washing alone, or by washing and steaming. Frequently, it is necessary to use a caustic spray in combination with the steaming operation, and, sometime, a detergent may be added to the water. Of course, low boiling liquids such as carbon disulfide, short chain aldehydes and ketones, etc., will again volatilize. Even fairly high boiling compounds will "steam-distill" when treated with steam.

The original concentration of each single commodity in the waste is relatively low; the amount is mainly a function of the degree of car drainage by the user, and of the viscosity of the product. It varies from 2 to 10 gal. and over, per car.

In the planned Saegertown treatment works, the cars will be divided into three categories, namely:

1. Those which have contained solid materials
2. Those which have contained soluble materials and compressed gases
3. Those which have contained insoluble materials and acids

Pressure tanks, incidentally, will only be repaired in General American's plant at Masury, Ohio (Sharon Plant No. 1).

Character of Wastes. As already pointed out, the waste is complex and variable in composition. In order to give a more accurate picture of its character, Tables 1 and 2 report the results of two surveys made at different periods in two large tank-car maintenance shops. The first represents a recent compilation prepared by GATC East Chicago plant No. 2, giving a weekly list of tank cars cleaned during the six-month period from Nov. 1, 1948, to April 30, 1949, arranged by commodities. The percentage of each commodity cleaned is shown during the above-mentioned period, based on the grand total of 1611 cars.

By classifying the products into solids; acids; alkalies; inorganic salts; petroleum products; oils, fats and greases of biological origin, etc., the following per cent figures are obtained:

TABLE 1(*a*)

Class	%	Commodities
Solids	23.66	13
Acids	5.52	4
Alkalies and alk. salts	3.97	3
Inorg. salts (neutral)	1.43	2
Petroleum products	31.29	7
Oils, fats, etc.	12.73	12
Sol. org. chem.	4.77	7
Insol. org. chem.	5.52	7
Insol. miscell.	4.78	7
Sol. miscell.	5.46	4
Compressed gases	0.87	1
	100%	67

These classes are placed in the categories corresponding to the primary segregation planned for the Saegertown shop, as follows:

NOTE: Complete Tables 1 and 2 are on file (Document 2835) with the American Documentation Institute, 1719 N. Street, Northwest, Washington, D. C. Obtainable by remitting 50 cents for a microfilm and 60 cents for photoprint.

Category	%
Solids	23.66
Liquids:	
Soluble liquids (all other commodities)	15.83
Insoluble liquids and acids	59.82

From the total of all *liquids*, the insolubles and acids represent about 80%.

The solids, in turn, are divided into combustible solids and incombustible solids, as follows:

Category	Treatment	%
Combustible solids	Incineration	15.47
Incombustible solids	Dumping (surfacing, etc.)	8.19

In order to show the variation in composition, Table 1(*b*), tabulation for the first four months of 1949 gives a picture of distribution of three classes of commodities, selected for their importance in the treatment method:

during the test period. The variations are apparent.

It will be noted that a comparison between the 6-month survey in East Chicago and the short survey in Masury shows some surprising differences, in so far as the distribution of commodities is concerned, as shown in Table 2(*b*).

The reason for these discrepancies is threefold. In the first place, a longer survey at Masury would have ironed out some of these differences. Secondly, there are seasonal variations, particularly in the field of agricultural and petroleum products. Finally, many specialized tanks (for instance, those engineered for shipping acetic acid, nitrogen fertilizer, nitric acid, caustic soda) are constructed of welded alloys (aluminum, stainless steel, etc.), and can be repaired only in the Sharon plant equipped for this type of work.

flow has been found to equal 6,250 gal./hr., or 50,000 gal./8-hr. day. It was obtained at the Sharon plant by measuring water consumption at the cleaning racks by means of flow meters over several periods.

TABLE 1(b)

Month	Total Cars Cleaned	Phenols, Tar Oil, etc. Cars	Phenols, Tar Oil, etc. %	Solids Cars	Solids %	Solubles Cars	Solubles %
Jan.	72	..	....	11	15.3	9	12.5
	79	1	1.27	11	13.9	13	16.2
	52	2	3.85	13	25.0	9	17.3
	52	2	3.85	18	34.6	5	9.62
	45	2	4.44	4	8.9	3	6.67
Feb.	68	4	5.88	10	26.5	15	22.1
	65	2	3.08	15	23.1	9	13.8
	59	3	5.08	12	20.3	12	20.3
	70	4	5.71	12	17.1	11	15.7
Mar.	77	3	3.90	21	27.3	15	19.5
	69	1	1.45	19	27.5	18	26.1
	66	3	4.55	14	21.2	13	19.7
	73	.	....	17	23.6	11	15.3
Apr.	72	.	....	11	15.3	12	16.7
	64	3	4.55	6	9.09	10	15.2
	50	3	6.00	9	18.0	7	14.0
	50	1	2.00	10	20.0	10	20.0

The second survey (Table 2) is a day-to-day tabulation prepared with the main purpose of collecting data on water and steam consumption in connection with the project to build a waste treatment installation at the company's Masury (Sharon) plant. It covers 18 days and lists only cars loaded with liquid commodities, to the exclusion of those which carried solids.

This survey, considered from the point of view of product distribution, shows that cars having carried taste-producing compounds (phenols, tar oils, etc.) were washed on four days out of 18. The heaviest concentration was when three such cars were cleaned.

The rearrangement shown in Table 2(*a*) gives a general picture of the frequency of the most typical groups

Quantity of Wastes.—Surveys were made previously at Masury to determine the average amount of wash water and steam consumed per hour in GATC's repair and maintenance plants. All of them were based on racks with 24 positions (10 positions on washing rack, 10 positions on steaming rack and 4 positions for acid cars), which is the full capacity of the Sharon plant.

The future Saegertown shop will have from 16 to 20 positions, so that the daily maximum flow figure can be reduced by at least 1/6. This maximum

TABLE 2(a)

Date	Insolubles: Petroleum Prod.	Insolubles: Chemicals	Insolubles: Fats, etc.	Acids: Org.	Acids: Inorg.	Solubles: Alkalies	Solubles: Org. Chemicals	Solubles: Other	Phenols
9/24	2	2				1	2	1	
9/25	1			2		1			
9/26	1	1				1	1		
9/27						1			
9/29						2	1	1	
9/30								1	
10/3			2	1					
10/4						2			3
10/6				1				2	1
10/7				1	1			1	
10/8				1		1		2	1
10/10				1				1	1
10/13	2								1
10/14								2	
10/15	1							1	
10/18								2	
10/21				1		1		1	
10/22				1	4	1			
	7	3	2	9	5	11	4	16	7

TABLE 2(b)

Product Last Hauled	% of Cars Cleaned at Sharon	% of Cars Cleaned at East Chicago
Crude oil, gasoline, fuel oil, etc.	9.0	31.3
Animal and vegetable fats, oils, soaps, etc.	0.0	17.6
Coal tar oil, creosote, phenol, etc.	7.7	9.3
Mineral acids	24.3	4.9
Acetic acid	11.5	0.4
Caustic and caustic soda	11.5	2.6
Nitrogen fertilizer	16.6	0.0

The amount of water used per car is, of course, a function of the commodity last loaded. Actual figures vary from less than 100 cu.ft. to 2000 cu.ft. (748 gal. to 14,960 gal.).

Steam consumption was checked twice over 60-day periods, wherein a record was kept of the number of cars steamed, time of steaming in hours and the amount of steam delivered to the steam rack, recorded through a Bailey flowmeter which was verified for accuracy before and after each 60-day test. It was found that a safe conservative figure was 4000 lb. of steam per car.

On the basis of 8-hour per day operations at the cleaning rack, and having 20 tank-car positions of which 10 are lined up for steaming and 10 for water washing, the total flow of waste will be as follows: Washing, 5650 gal./hr.; steaming, 600 gal./hr., making 6250 gal./hr. and 50,000 gal./day for an 8-hr. day.

It should be noted that all the positions are practically never occupied in any single day. In GATC's Colton plant (6 positions, not including the three-car rack for sodium compounds) it took more than two weeks to fill the 50,000 gal. equalizing and collecting basin before the treatment works were started; and, since that time, the waste installation is being run about three times per month, the average number of cars cleaned being 44, or 1.5 per day (one year operation). A rapid perusal of Tables 1 and 2 will confirm this statement. Table 2(*c*) shows the figures for the Sharon plant:

Table 2(*c*) (as well as the East Chicago plant, 1949 survey and the Colton experience) shows that, in actual practice, about 50% of the cleaning-rack capacity is used.

It can, therefore, be safely stated that the actual flow will correspond to about half the capacity of the cleaning racks, i.e., 25,000 gal./day. The waste treatment works are designed for a 70,000-gal. daily capacity, which represents a safety factor of 40% over and above

TABLE 3(c)

Date	Cars Washed Only	Cars Steamed Only	Cars Washed and Steamed	Total
9/24	5	2	–	7
9/25	4	–	–	4
9/26	4	–	–	4
9/27	1	–	–	1
9/29	3	1	–	4
9/30	1	–	–	1
10/2	1	–	–	1
10/3	–	2	1	3
10/4	2	3	–	5
10/6	3	2	–	5
10/7	3	–	–	3
10/8	4	2	–	6
10/10	3	–	1	4
10/13	1	–	2	3
10/14	1	2	–	3
10/15	2	–	–	2
10/16	2	–	–	2
10/21	6	1	–	7
10/22	4	4	–	8

the maximum average flow, and of 280% over the actually expected daily quantity of waste discharged in 8 hours from the maintenance plant. This means that the holding space, as provided, will also act as equalizing basins, collecting the waste from 2-3 days of cleaning operations.

Treatment Process

Principle, General Outline. The treatment process is a combination of standard methods and of new principles (see Flow Diagram). The cars are first segregated into three categories, according to the nature of their last load, namely, (1) Products which are solid at ordinary temperature, or aqueous suspensions of such solids, (2) Liquid commodities, immiscible with water, insoluble or only slightly soluble, and acids, and (3) All other materials.

Category 1 (solids) in turn, is subdivided into (a) combustible products; (b) incombustible products. The first group (a) is to be incinerated, while the second group (b) can be simply dumped (clay slurry, sand, etc.).

The wash waters from category (2) are treated alternately (for periodic cleaning purposes) in one of two mechanical oil separators (Gale Interceptor) in order to remove the largest part of the free insolubles, such as turpentine, vegetable oils, animal oils, liquid petroleum products, which are collected and stored for use as a fuel complement (to produce the steam needed at the cleaning racks). It should be noted that the acid reaction of the wastes during this first phase helps prevent the formation of emulsions, decreases the solubility of alcohols and phenolic compounds, and enhances substantially the mechanical separation of all hydrophobic liquids, by creating conditions which are generally antagonistic to solvation.

The underflow from the mechanical oil separators is then conditioned in an agitator with powdered coal for the next step. This consists roughly in adsorption of dissolved and emulsified hydrophobic compounds on the surface of finely ground coal, and subsequent separation of the latter by froth flotation (patent pending).

The basic principle of that operation can be shortly explained as follows:

Many solid materials exhibit a particular surface property called water-repellency (hydrophobia). While quartz, for instance, will be wetted by a water film (a drop of water will spread to form a flat disc), carbon, talc, sulfur, etc., will remain dry (a drop of water will stay on the surface as a spheroid, slightly flattened at top and bottom). This phenomenon actually results from a competition between air and water, "where the latter looses out." It can be correctly said that hydrophobic solids are wetted by air and other gases as well as by all hydrophobic liquids. When such a solid (sulfur, coal, paraffine, etc.) is brought into contact with an emulsion or even a solution of hydrophobic compounds in water, it will extract them by adsorbing these organic compounds, thus still increasing its own water-repellency. The larger the surface of the solid (in other words, the finer its particles), the larger the quantity of adsorbed hydrophobic liquid per unit weight. If, now, air is introduced into the pulp as a fine dispersion of bubbles, these latter will compete with the water and become attached selectively to these solid particles coated with a thin film of highly water-repellent liquids. This agglomerate of air and minute solids has a lower specific gravity than water, and will therefore rise to the surface. If, moreover, a reagent (frother) is added to stabilize the foam thus produced, this froth can be separated by scraping, and discharged into a launder for disposal or further treatment.

This principle is used industrially on a large scale for the concentration of ores and the cleaning of coal by froth flotation. In this case, of course, a collecting reagent (i.e., phenols, fatty acids, and many polar-nonpolar organic compounds) are added in sufficient quantity to the pulp (suspension of finely ground ore in water), in order to condition the surface of the solid for its selective attachment to the air bubbles. In the case of tank-car wash waters, the collecting reagents are already present, and ground coal has to be added as the solid adsorbent.

The best pH for the adsorption of phenols, fatty acids, nonpolar oils, etc., on coal is below 7.0 (preferably between 4.5 and 6.5). This is the second reason for which the wastes containing hydrophobic liquids are combined with those containing acids. The third reason is the fact that flotation of coal is best either in an alkaline (pH 8.5 – 10) or in an acid (pH 4.5 – 6.5) circuit.

It is obvious that this process (eventually followed by a standard chemical or biological treatment) is generally applicable to the treatment of low phenolic wastes and to the removal of hydrophobic liquids from emulsions, as often produced in other industries. Experimental work on refinery, cokery and chemical manufacturing wastes (D.D.T. production, vegetable oil processing, etc.) has shown that the same principle can be used successfully in these fields. The one critical limitation is the amount of coal necessary for the adsorption.

Returning to the general outline of the treatemnt process: the acid waste is mixed in a Turboconditioner* with coal previously wet-ground to at least –35 mesh (over 50% –200 mesh), while the pH is adjusted to 4.0-6.0. The slurry as obtained it then fed to a series of three Turboflotters, where it is treated with finely dispersed air bubbles. A frother, such as pine oil, cresylic acid, American Cyanamid Co.'s B-23, B-60, etc., is added into the first cell, in order to stabilize the foam. The fine coal concentrate is scraped off and filtered, producing a coal and oil cake at 25-35% moisture, which is mixed with enough coarse dry coal to be burned under the main boiler.

The flotation tailings flow into a series of three Turboaerators, where they are treated together with the waste of category (3), hydrophilic liquids other than acids.

After these wastes of group (3) have been collected in an appropriate holding basin, they are pumped in metered amounts to the first aerator, while a sufficient amount of ferrous sulfate is added to form a good floc when the pH is sufficiently raised. The acid flotation tailings also contain dissolved ferrous sulfate and other iron salts (due to tank-car corrosion). The mixed wastes are first thoroughly aerated (oxidation of many organic compounds) in acid medium. Then, by means of an automatic control, enough lime is added to form gelatinous ferrous hydroxide, and nearly to neutralize the waste. This ferrous hydroxide, as is well known, will "entrap" the colloids in suspension and adsorb most of the organic materials contained in the liquor. The aeration is continued in neutral medium, producing oxidation of the ferrous to the ferric hydroxide (actually, the ideal compound for fast settling is ferroso-ferric hydroxide), and catalytic induced oxidation of the organic compounds still in solution.

The waste is finally discharged into a thickener or clarifier, in order to separate the iron hydroxide flocs, loaded with adsorbed impurities, from the clear overflow. The thickener overflow, representing the effluent from the primary waste treatment, will be lagooned. It will then be given refined biological treatment by bleeding it continuously (i.e., during 24 hr.) at a controlled rate into a recirculating trickling filter installation, together with the sanitary sewage produced by the labor force of 150-200 workers.

This secondary biotreatment is actually a superfluous precaution, insofar as the immediate problem of stream pollution is concerned. However, from a strictly legal point of view, it has to be installed, in view of the rulings of the Sanitary Water Board of the Commonwealth of Pennsylvania, which prohibit the discharge of either raw sewage or any phenolic substance to any stream of the state. (Note that, contradicting these requirements, the Borough of Saegertown has no sewage works for a population of more than 2000!)

The thickener underflow will be lagooned (and, should this prove necessary, would be filtered and calcined in the incinerator).

An example, describing the treatment of a sample of combined waste from the East Chicago plant in General American's research and testing laboratory, will serve as an illustration of the process. About 20 gal. of wash water

* The Turbo equipment is designed and manufactured by Turbo Mixer Corp., a unit of the Process Equipment Division, General American Transportation Corporation.

TABLE 3.—RAW WASTE
(Influent to treatment installation)
Analysis in p.p.m.

A.—Before sludge settling and oil separation. B.—After sludge settling and oil separation.

Sample No.	Provenience	Type	Organic Matter (Oxydizable[1] $KMnO_4$)	Ether Extract[2]	Phenols and Aromatic[3]	Suspended Solids[4]
3	East Chicago	A	.....	770.8	18.3	3108
		B	256.1	.....	18.3	1673
6	Sharon	A	.....	1021.3	24.2	10400
		B	402.6	23.3	24.2	.....
7	East Chicago	A	.....	670.0	21.8	2873
		B	267.6	21.3	21.8	.....
9	Sharon	A	.....	1132.3	10.2	9238
		B	382.5	.....	10.2	.....
10	Los Angeles	A	.....	710.6	....	2823
		B	202.4	.....	....	.....
11	Los Angeles	A	.....	532	....	2241
		B	198.7	.....	....	.....
12	Colton	A	.....	600.8	....	2777
		B	210.2	18.2	....	.....
16	Sharon	A	.....	623.3	25.1	9148
		B	251.7	21.3	25.1	.....
18	Sharon	A	.....	942.4	21.0	8894
		B	273.8	24.1	21.0	.....
21	East Chicago	A	.....	810	32.1	2594
		B	281.3	.....	32.1	.....
23	East Chicago	A	.....	603.4	22.8	2651
		B	266.3	.....	22.8	.....
25	East Chicago	A	.....	594.1	23.2	2682
		B	274.4	20.2	23.2	.....

[1] Scott's Standard Methods of Chemical Analysis: Sanitary Analysis of Water-Oxygen Consumed.
[2] Scott's Standard Methods of Chemical Analysis: Water Analysis for Oil—p. 2078.
[3] Commercial Methods of Analysis by Snell and Biffen: Indophenol Method for Phenols.
[4] Gooch Method.

were secured from the East Chicago plant. This liquid was taken 2-3 ft. below the surface of the present collecting pond and represents a true average sample of strong waste, without original segregation of any sort. (*See* Sample No. 25, Table 3.)

Six liters of waste water were placed in a large laboratory flotation cell (capacity: 9 l.). The pH was adjusted to 5.5 by addition of sulfuric acid (75 cc. H_2SO_4 10% by vol.). 150 g. of soft coal (plant fuel), previously ground to —100 mesh (dry grinding and screening), which had been soaked in water overnight to be made thoroughly wettable, were added, and the pulp conditioned for 10 min. The pH was checked again, and found to be unchanged (5.5).

Four droplets of frother No. 60 (American Cyanamid Co.) were added, and conditioning continued for 45 sec. Flotation was started, and 2 droplets of frother added periodically after 2 min. of foam discharge. Total flotation time: 9 min. Total frother: 10 droplets. Volume of concentrate collected was about ±1.5 l.

Ferrous sulfate was then added to the flotation tailings in an amount corresponding to 9 lb. $FeSO_4 \cdot 7H_2O$/ton (23 g. total). The mixture was aerated in the cell for 10 min. A lime slury was added by small amounts, while agitating (this operation took about 5 min.), to a pH of about 6.5.

The suspension of ferrous hydroxide was aerated for 6 min., and thereby oxidized to the ferric state (total aeration time: 10-12 min.). The tailings amounted to 5500 cc. (1000 cc. dilution). They were settled in several cylinders, giving 800 cc. of underflow and 4700 of overflow. Analysis of the products, shown in parts per million (ppm) is given in Table 4.

Composition of Primary Treatment Works by Units in Line of Flow

The composition of the planned treatment works is shown in the Operation Layout.

A. *Solids* (Cleaning Rack No. 1)—Solids of mineral (inorganic) nature, such as sand slurries, clay suspensions, etc., are simply dumped into a shallow basin. Solids of organic nature, such as asphalt, creosote, etc., are melted with superheated (dry) steam and drained. The residue is mechanically removed. A solvent cleaning process is presently being developed. If the cars finally have to be washed or steamed, the condensate and water are treated with the insoluble liquids. The excess of combustible organic solids will be incinerated, using possibly a small Goder Furnace.

B. Insoluble Liquids and Acids (Cleaning Rack No. 3)—These wastes flow first through two cement settling chambers, in order to remove any heavy sludge; then alternately through one of two Gosco Interceptors (Gale Oil Separators) No. 9, with a rated capacity of 300 gal./min. each.

The overflow of the Interceptors (oils, etc.) is pumped, by means of a 0-20 gal./min. pump, to oil storage tanks for use as fuel complement. The underflow is discharged into a 50,000-gal. covered cement holding basin, with sloping bottom and shallow sump. A 40-gal./min. centrifugal pump is provided to bring the waste from this storage and equalizing tank to the treatment works proper. The 40-gal./min. pump is connected to a ball float through a lever operated switch, which starts the ¾-hp. motor of the pump when the liquid level reaches 2 ft. below the top. Operation stops when the liquid level reaches 2 ft. above bottom. The waste then flows to a baffled Turboconditioner No. 7, 22-in. Duplex impeller, 125 rev./min., 10 min. retention time, where it is mixed with coal slurry and with returning filtrate from the coal flotation concentrate.

Said coal slurry is prepared as follows: The coarse coal is stored in a bin No. 1 (capacity 5 tons), from which it is fed, by means of a Hardinge 30-in. disc feeder No. 2 to a Hardinge conical ball mill 3 ft. × 8 in., No. 3. This mill is definitely oversized for grinding about 500 lb. of coal/hr. to —35 mesh, and will actually produce a much finer discharge (tests show more than 50% —200 mesh). The slurry is collected in an 800-gal. tank No. 4, provided with a float control for water supply to produce a 1:1 pulp. This is pumped through a hydroseal rubber-lined pump, capacity 0-10 gal./min., to a 35-mesh vibrating screen No. 5, where the oversize is separated and returned to the ball mill. The undersize flows to a Hardinge constant weight dip feeder No. 6, which discharges the fine coal suspension into the Turboconditioner No. 7. The pH of the Turboconditioner overflow is measured by a Beckman cell, and the resulting electrical impulse, amplified through Indicator relay type *K* is transmitted to an automatic diaphragm valve (¼-in.) with a range from 0 to 0.1 gal./min., admitting sulfuric acid to the Turboconditioner, in order to maintain the pH therein at a value of 5.5-6.5. The acid (concentrated) is contained in a 200-gal. tank No. 8, equipped with a centrifugal pump (0 to 4 gal./min.), recirculating the excess reagent. The effluent from the Turboconditioner flows into a bank of three Turbo flotation cells No. 12 equipped with 12-in. impellers (190 rev./min.). A reagent feeder supplies the small amount of frother (0.0013 gal./min.) required to stabilize the foam. This latter is scraped off by 26-in. D. paddles into two pitched troughs, and pumped by a booster pump (0 to 15 gal./min.) to feed a 12-compartment rotary vacuum filter 3 ft. × 3 ft. No. 14. The wet filter cake is stored in a 5-ton bin No. 15 for subsequent mixing with dry coal and burning as a boiler fuel. The filtrate is collected in a receiver tank No. 10, and returned to the Turboconditioner by means of filtrate pump (0 to 10 gal./min).

C. Soluble liquids, etc. (All Other Commodities)—These wastes are collected in a

TABLE 4.—TREATED WASTE
Analysis in p.p.m.

F.—Flotation method. P.—Precipitation method.

Sample No.	Provenience	Treatment	Organic Matter (Oxydizable[1] $KMnO_4$)	Ether Extract[2]	Phenols and Aromatics[3]	Suspended Solids[4]
3	East Chicago	F	52.7	4.2	7.00	98
		P	32.4	5.0	.....	zero
6	Sharon	F	48.3	7.3	5.21	261
		P	34.8	8.0	.....	0.02
7	East Chicago	F	47.7	4.2	6.79	124
		P	30.0	6.8	.....	0.01
9	Sharon	F + P	25.3	7.6	1.52	zero
10	Los Angeles	P	31.4	5.0	.....	zero
11	Los Angeles	P	32.3	6.8	.....	0.03
12	Colton	P	29.1	4.5	.....	zero
16	Sharon	F	46.7	8.1	5.12	116
18	Sharon	F + P	26.8	6.9	1.96	zero
21	East Chicago	F + P	25.7	7.7	1.67	0.01
23	East Chicago	F + P	28.2	8.1	1.99	zero
25	East Chicago	F + P	27.3	7.8	1.75	zero
		F	.....	.....	1.25	.....

[1] Scott's Standard Methods of Chemical Analysis: Sanitary Analysis of Water-Oxygen Consumed.
[2] Scott's Standard Methods of Chemical Analysis: Water Analysis for Oil—p. 2078.
[3] Commercial Methods of Analysis by Snell and Biffen: Indophenol Method for Phenols.
[4] Gooch Method.

holding and equalizing basin of 20,000-gal. capacity. From there, they are pumped, by means of a centrifugal pump, into the discharge box of the last flotation cell. The pump has a variable capacity from 0 to 20 gal./min., and is controlled by a float located in the first of three aeration cells No. 13 through a switch-and-valve system. About 9 lb./hr. of hydrated ferrous sulfate (in the form of a saturated solution) are injected into the stream of this waste by a centrifugal pump (0 to 4 gal./min.). The reagent is stored in a 50-gal. tank No. 17, equipped with an open tilted Turboimpeller.

Tank No. 18 contains sulfuric acid, which can be used to neutralize, by manual control, alkaline waste from the 20,000 gal.-holding tank, in case the soluble liquids are treated separately.

D. Flotation Tailings and Soluble Waste. Tailings from the flotation operation, leaving the third flotation cell through a discharge box, are mixed therein with the soluble waste from the above-described 20,000-gal. holding tank. The mixed wastes are then aerated in the three cells No. 13, equipped with three 27-in. hooded Turboimpellers (125 revolutions per minute), inducing a violent and homogeneous aeration. The overflow from the last aeration cell is tested by pH electrodes, and the resulting electrical impulse, amplified through Indicator relay type *R*, is transmitted to an automatic diaphragm valve (½ in.) with a range from 0 to 5 gal./min., admitting a 10% lime slurry from tank No. 16 to aeration cell No. 13-2, or No. 13-3, in order to neutralize the excess acid and keep the pH at a constant value between 6.0 and 7.5, high above the precipitation point of ferrous hydroxide. This hydroxide, as well as organic matters in solution, are oxidized. The overflow from the last aerator then runs by gravity to a thickener, No. 19, 35 ft. in diameter and 12 ft. deep (retention time 15 hr.). The underflow from the settler will be discharged into a basin (from which it can be, eventually, disposed of by any suitable process). The clear overflow is collected in a 150,000-gal. earthen lagoon, from which it will be bleeded continuously at a controlled rate by means of the effluent pump (0 to 20 gal./min.), over 24 hr. or more, into the sewage treatment plant (trickling filter) provided to take care of the employment population of 200, for refined treatment. This will result in a regulated discharge of the purified waste into the stream over a 24-hr. period (maximum dilution).

Primary Treatment and Experimental Results

The operation of the above-described waste treatment works will be mostly discontinuous. It is doubtful whether the total amount of waste produced in a single 8-hr. day will ever be above 30,000 gal. Generally, as shown under *Quantity of Wastes* it is expected to vary from as low as 800 gal. to 25,000 gal./day. As the liquid level in the holding basins is the determining factor, a float control in these pools will actuate a signal when a critical point is reached. An electric timer will start the 40 gal./min. sump-pump and the whole plant about 25 minutes later, while the pump in the 20,000 gal.-holding tank is controlled by a limit float in aeration cell No. 13, and will start only when a certain level is reached in that tank (and stop when the liquid overflows into a by-pass launder through a limiting slit). All motors, of course, can be started by hand, and it is therefore possible, for instance, to treat the contents of the 20,000-gal. holding tank independently from the waste collected in the 50,000-gal. basin.

The pH control is automatic throughout the plant, and can be set at any value, for instance from 6.0 to 8.5 for the final effluent. All other reagent feeders are independent, and allow a sufficient range. One operator is required per shift, in order to check reagent levels in the tanks, adjust the coal feeders, the frother, etc.

Tables 3 and 4 show the analysis of a series of raw waste samples, and the results obtained by treating them in the laboratory or pilot plant by the methods just described.

It should be noted that all these samples contained the *total* waste from tank-cleaning operations (insoluble *and* soluble liquids, alkalies and acids). This is due to the fact that no segregation has been practiced to this date in any of the GATC repair and maintenance shops, except in the most recent plant in Colton, Calif.

Sample 3 represents an average mixture collected over three weeks, at the rate of one gallon every hour, at East Chicago Plant No. 2. Sample 4 is a two-month collection from Sharon as above. Sample 7 has been taken out of the first lagoon, where all waste waters from tank-car washing are presently collected in the East Chicago plant. Sample 9 is a three-week collection in Sharon, and Samples 10 and 11 are two-week collections in the former Los Angeles plant (now replaced by the Colton Shop). Sample 12 is a two-week collection in Colton; sample 16 is a three-week collection in Sharon, sample 21 a four-week collection in East Chicago, while samples 23 and 25 again originated in the collecting lagoon.

Insofar as the treatment of the soluble liquids is concerned, experience since February, 1948, in the West Colton (Calif.) plant with complex wastes containing insoluble liquids and acids as well as solubles, but no aromatics or toxic materials, using the precipitation method alone (iron sulfate, lime, aeration and sedimentation) proves that the results to be expected are exceptionally good (*5*). The water from a specially constructed test well (following specifications of the California Sanitary Water Board), upon weekly analyses by the local health authorities, has shown only a slight increase in calicum sulfate, but no pollution whatsoever.

Insofar as the flotation method is concerned, oil removal is suitable (better than 8 p.p.m. in effluent). The precipitation method, moreover, is actually an adaptation of an analytical procedure for oil determination in waste water, and should, therefore, be practically quantitative. The reduction in organic matter (oxidizable by permanganate) is good by both methods. Their combination results in a pollution load of 25-30 p.p.m. in the effluent. The reduction in phenol content by the flotation method is about 90% for wastes containing up to 100 p.p.m. of the compound, i.e., in our case from 30 p.p.m. to 3 p.p.m. or better. Additional aeration reduced this figure further to about 2 p.p.m.

In other words, the effluent of the primary treatment plant will not exceed 30 p.p.m. oxygen consumed, 8.5 p.p.m. ether extract and 7 p.p.m. phenol. It will be substantially free of suspended solids. On the average, these values will be lower, as shown by Table 4.

Secondary Treatment

In order to improve still further the character of the industrial waste discharged from the above-described installation, and to conform to Pennsylvania Health Department regulations, a refined treatment is required. This could be either chemical or biological. In the first case, overchlorination and active carbon filters, or, still better, the application of chlorine dioxide, would probably give satisfactory results.* In the second case, trickling filters would be used.

As Pennsylvania's State laws prohibit the discharge of untreated sewage into the streams of the Commonwealth, adequate works for the purification of the sanitary sewage produced by a 150-200 working population to be employed by the Saegertown repair and maintenance shops would be required, independently from any production of industrial waste. Cooperation with J. R. Harvey, sanitary district engineer in Meadville, Pa., led to the conclusion that, under the given circumstances, it was both logical and more economical to combine the refined treatment of the effluent from the industrial primary treatment installation with that of the sanitary sewage from the proposed shops.

A study (*9*) was then made by Ted R. Hazeltine of The Chester Engineers, Pittsburgh, Pa., acting as consultants for GATC, in order to review the problem of combined biological treatment of sanitary sewage and effluent from the industrial waste installation.

The following data are largely taken from this report (*9*).

Volume of Sanitary Sewage, Its Character and that of Effluent from Primary Treatment Plant.

* A system using oil separation, chemical precipitation and adsorption (magnesium sulfate and lime), followed by treatment of the clarified effluent with chlorine dioxide, is being installed presently in the GATC East Chicago Plant No. 2. The last step will be closely studied as to its efficiency, and, if successful, might be applied elsewhere.

TABLE 5.—SUMMARY OF CHARACTERISTICS OF WASTES TO BE TREATED BIOLOGICALLY

	Volume gal./day	Rate of Flow gal./min.	5-Day B.O.D. p.p.m.	5-Day B.O.D. lb./day	Suspended Solids p.p.m.	Suspended Solids lb./day
Chemically Treated Industrial Wastes						
Maximum	70,000	55-60[1]	----	----	0	0
Minimum	0	----	----	----	----	----
5-day av.	33,400	23	100[2]	28[2]	0	0
7-day av.	23,900	16.6	100[2]	20[2]	0	0
Raw Sanitary Sewage						
Maximum	6,000	50	400	20	520	26
Minimum	0	----	----	----	----	----
5-day av.	4,000	8.4[3]	240	8	360	12
7-day av.	2,950	2	240	5.7	360	8.6
Screened Sanitary Sewage[4]						
Maximum	6,000	50	380	19	488	23.4
Minimum	0	----	----	----	----	----
5-day av.	4,000	8.4[3]	228	7.6	324	10.8
7-day av.	2,950	2	228	5.4	324	7.8
Design Flow (Exclusive of Recycle)						
A—Maximum: 7-day av. ind. + max. screened sewage	29,900	67	150	39	90	23.4
B—Normal: 7 day av. ind. + 5-day av. screened sewage	27,900	19.2	119	27.6	47	10.8
C—Av.: 7 day av. of ind. + screen sewage	26,750	18.6	114	25.4	25	7.8

[1] Depends on pump capacities at holding tanks; figure given is based upon assumed capacities of 40 gal./min. at 50,000-gal. tank and 15 to 20 gal./min. at 20,000-gal. tank.
[2] No data available on actual B.O.D. of chemically treated wastes; all calculations based on an assumed value of 100 p.p.m. which should be checked before undertaking actual design.
[3] On the basis of an 6-hr. day.
[4] Fine screen assumed to remove 10% of suspended solids and 5% of B.O.D.

The average amount of sanitary sewage, based on a working population of 150 persons, to be later increased to 200, is estimated at 4,000 gal./day, containing 8 lb. (or 240 p.p.m.) of B.O.D., and about 12 lb. of suspended solids. The effluent from the primary treatment installation, on the other hand, will average 5 p.p.m. of phenols and 30 p.p.m. O.C. (chemical oxygen consumed).

Unfortunately, the relationship between biochemical oxygen demand (5 day B.O.D.) and chemical oxygen consumed (O.C.) in industrial waste of variable composition is absolutely inconsistent. As a yardstick for measuring the efficiency of a treatment process for trade waste, the O.C. can be considered an excellent measure. However, all criteria for judging ability of a receiving stream to handle a given pollution load are based on B.O.D. Ratios of B.O.D./O.C. for industrial wastes range from 0.34 to 10.25. Analyses of three different, undiluted and untreated samples of the East Chicago plant waste, with particularly high B.O.D. values, gave the following figures:

Sample No.	5 Day B.O.D.	O.C.	Ratio B.O.D./O.C.
1	1140	300	3.80
2	1260	400	3.15
3	590	1300	0.45

A treated sample of tank-car waste (precipitation method only) gave a B.O.D. of 82, and a O.C. of 46.3 (Ratio: 1.77). An average sample (taken over 2 weeks) and pretreated in the laboratory (flotation and precipitation) gave a O.C. of 27.8 and a B.O.D. of 72.3 (Ratio: 2.6).

For the design of the Secondary Treatment (combining biological treatment of sanitary sewage together with effluent from primary industrial waste installation) a B.O.D. value of 120 p.p.m. has been assumed for the pretreated tank-car wash water.

Biological Treatment of Phenolic Wastes. Phenolic compounds, being odor-and-taste producing, are among the worst offenders in stream pollution. It is therefore desirable to eliminate completely these chemicals, before discharging an effluent containing such aromatic compounds from a waste treatment works into the stream.

A study of the literature (*1-3, 6-8, 10-12*) shows that phenols can be destroyed by ordinary biological filters, if present in relatively small amounts (i.e., up to 55 p.p.m.). The Dow Chemical Co. purifies wastes averaging 50 p.p.m. phenol by biofiltration, claiming an efficiency of 50 to 90%, depending upon temperature (*7*). Eldridge (*1*), when treating a mixture of river water and pure phenol, found that complete removal could be obtained in one operation with an influent containing up to 30 p.p.m. phenol; while, if the initial effluent was again applied to the filter (recirculation), complete destruction of the chemical could be obtained even with an initial phenol content as high as 180 p.p.m. The work by Ettinger and Ruchhoft (*3*) also shows that sewage polluted water is required for the rapid oxidation of phenols. Moreover, if the water has been subject to recent phenolic pollution and recovery, the rate of destruction is substantially increased.

Biological Treatment Installation. Table 5 summarizes the volume and composition of the component wastes to be treated in the sewage plant, and the total flow on which its design is based.

The thickener overflow from the Primary Treatment installation is collected in an earthen lagoon with a capacity of 150,000 gal. This will equalize the character of the pretreated wastes, avoid "slugs" of undiluted products toxic to biological life, and allow a storage of 5 days or better. The lagooned fluid will be fed continuously, at a rate of 17 gal./min., to a pump-well of 6000-gal. capacity, equipped with two 55 gal./min. pumps. The sanitary sewage will be fed to a drum screen at the rate of from 0 to 50 gal./min. Recycled filter effluent will be also fed to the screen at a rate of 43 to 93 gal./min. The screened sewage and recycle, with a constant rate of 93 gal./min., will be mixed in the pump well with the chemically treated industrial effluent. The mixed wastes will be fed continuously to a trickling filter, 26 ft. in diameter, with a media depth of 6 ft. The filter effluent will flow into a sedimentation basin having an area of 100 sq.ft., a volume, above pyramidal bottom, of 3,750 gal. and an effluent weir length of 20 ft. Based upon the maximum expected flow of 67 gal./min. through this basin, it would have a theoretical settling rate of 960 gal./(sq. ft.)(day), with a detention period of about 56 min. and an overflow rate of 3.35 gal./(min.)(foot of weir). The amount of filter effluent recycled will be automatically regulated by a float-controlled butterfly valve located in the pump well, and so adjusted as to maintain a constant water level in that well regardless of the rates of inflow of trade wastes or sewage.

The B.O.D. loading per acre foot on the filter will be 540 lb. under extreme conditions, and about 380 lb. under normal conditions. It is expected that the installation as described will remove at least 85% of the applied B.O.D., and reduce the phenol content to less than 1 p.p.m.

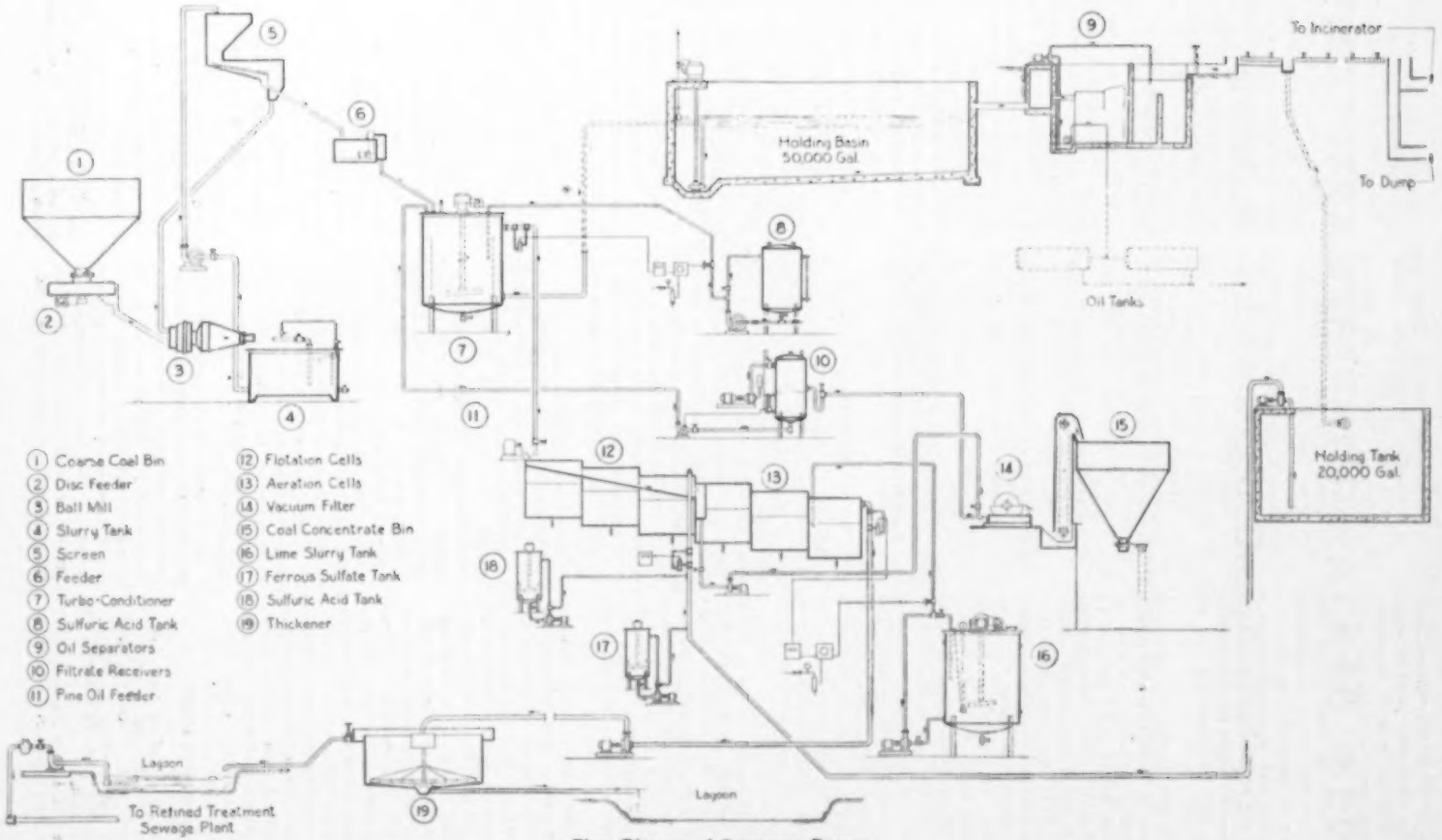
Expected Results

French Creek, into which the Saegertown plant will discharge its treated wastes, has a drainage area, above that borough, of 629 sq. mi. The total fall of the river in the 36-mile stretch between Saegertown and Franklin, where the creek joins the Allegheny River, is about 120 ft., or a little more than 3 ft./mile.

The city of Franklin utilizes the creek as a source of public water supply and has its intake located about 2 mi. above the mouth of the creek. From the meager data available, a velocity of about 0.83 mi./hr. has been calculated for the time of flow from Saegertown to the Franklin intake. On that basis, the treated wastes discharged from the projected plant would reach the Franklin intake in 29 hr.

There are two critical periods to be considered during the year. "The first and most obvious is the period of July to September, when stream flow is at a minimum and water temperatures at a maximum. Under these conditions organic pollution, as measured by the B.O.D. test, is the most serious because not only is the quantity of dilution water at a minimum, but biological oxidation is also accelerated due to the high temperatures. Data published by the Department of Forests and Waters (*3*) indicate that the water temperature during July reaches a maximum of 80° F. and averages 71° F.

The second critical period occurs during January to March, inclusive, when stream flow is at a maximum and water temperatures are just slightly above



Flow Diagram of Treatment Process.

freezing. Under these conditions pollution of the creek with phenolic wastes is most likely to result in the production of taste and odor difficulties in the Franklin water supply. Stream velocities are higher so there is less time available for the stream to assimilate or oxidize the phenolic compound, and at the same time biological action is retarded due to the low temperatures and hence much longer periods would be required for the oxidation of the phenols." (*9*)

Even by discharging into the Creek a maximum of 70,000 gal. of chemically treated wastes containing 100 p.p.m. or about 60 lb. B.O.D. and 7 p.p.m. or 4.1 lb. phenol, over a 24-hr. period, together with 6,000 gal. of raw sewage containing 20 lb. B.O.D. over 8 hr., the B.O.D. loading on the river would be equivalent to 120 lb./day, or only about 1 p.p.m. at Saegertown. It is obvious that the stream could handle that pollution in a mile or two of travel. Phenol concentration would be 35 parts per billion at Saegertown, but even without oxydation, it would only be 12 p.p.b. at Utica. "The time of travel from Saegertown to Franklin might be 5 to 10 days which according to the data of Ettinger and Ruchhoft (*5*), should be ample time to oxidize 75 to 100 per cent of the phenol at summer temperatures, so that, at worst, not more than 3 p.p.b. would reach the Franklin intake. Under winter conditions, the minimum stream flow at Utica is about 350 ft./sec., so without oxidation, the phenol content would not exceed 2.2 p.p.b. there, or about 2 p.p.b. at Franklin. Most of the time phenols would be completely absent."

"Therefore, from a purely technical viewpoint, storage and uniform discharge of the totality of sewage and wastes produced in the plant over a 24-hr. period, 7 days a week, would probably prevent phenolic pollution of the Franklin intake or any detectable increase in B.O.D. of French Creek a mile below the point of their entrance (*9*)." However, this would not satisfy the letter of the law, and suppress a safety factor for variations, future expansion, etc.

It is believed that the above-described combination of chemical and biological treatment of the wastes will completely eliminate phenols and reduce the average B.O.D. to less than 5 p.p.m.

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Discussion

Harold L. Jacobs (Du Pont Company, Wilmington, Del.): Are you able to accumulate tank cars containing similar types of materials, or is it necessary that you take them as they come and get rid of them as fast as possible?

G. Gutzeit: The answer is yes to the last part of your question. It is rarely possible to accumulate tank cars containing similar commodities over a long period, in view of segregation. But, in a limited way, this can be done and is being done.

Anonymous: You said this would not work on removal of phenol if there was a high concentration of calcium salts. What is the limiting factor; what is the point?

G. Gutzeit: Calcium salts and other inorganic cations in excessive amounts will act as depressing agents in the coal flotation process. In other words, in the presence of a high concentration of inorganic ions, the adsorption capacity of coal for phenol and other organic compounds is decreased. A large percentage of soluble calcium salts, alkali sulfates, etc., is objectionable.

Anonymous: If you had 9,000 p.p.m. calcium chloride and 30 p.p.m. of phenol, then what?

G. Gutzeit: A concentration of 9 per thousand, or roughly 1% of calcium chloride would probably be acceptable. In practice, it is always possible to increase the adsorption capacity of the coal by increasing its relative amount, or, on the other hand, by decreasing its particle size. Obviously, the adsorption capacity is a direct function of the available active solid surface. The only limit is of economical nature. If more coal is used as an adsorbent than the plant boiler house can consume, the operation is a failure.

For instance, the planned Saegertown works, treating a maximum of 70,000 gal. of industrial waste water per 8-hour day, will require a maximum of 500 lb. of coal/hr., or 2 tons/day. This amount of coal can be easily utilized in the boiler producing the steam for the cleaning racks.

W. W. Hodge (Mellon Institute): What size of coal do you use?

G. Gutzeit: In the Saegertown plant, the grinding equipment is specified for 100% 35 mesh. It comprises a 35-mesh classifying screen, in closed circuit with an oversized ball-mill. Actually, there will be over 50% −200 mesh particles in the product. For the pilot plant tests described in the paper, −80 mesh to −100 mesh coal was used.

W. W. Hodge: Is the kind of coal important; must it be anthracite?

G. Gutzeit: Yes, the type of coal is important, although not critical. We have found that anthracite, for instance, is not as effective as soft coal. Among the various soft coals, in turn, there are slight differences in adsorption efficiency. The best type can easily be selected on the basis of an experimental determination of adsorption capacity and floatability.

W. W. Hodge: Have you actually run any experiments using the chlorine dioxide for destroying the phenols?

G. Gutzeit: Not yet. Our hope is based on published evidence. We are presently building a waste treatment plant in East Chicago, where we will use chlorine dioxide for the purpose of destroying the phenols. We expect to have experimental results this year (1950). The biological removal of phenols is well known. Concentrations up to 180 p.p.m. can be handled in a recirculating trickling filter.

J. M. Thompson (Minnesota Mining and Manufacturing Co., St. Paul, Minn.): You stated there were about 150 people employed at the site of this plant. Can you give us some breakdown on just what these persons are engaged in?

G. Gutzeit: Repairmen, tank-car cleaners and general service workers.

J. M. Thompson: Primarily then, is the greater proportion of them involved in repair of tank cars or cleaning?

G. Gutzeit: The major proportion will be involved in repairing tank cars. The cleaning crew consists of about 10 men per shift.

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HEAT TRANSFER IN PACKED BEDS

Analytical Solution and Design Method

Fluid Flow, Solids Flow, and Chemical Reaction

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This paper discusses the transfer of heat in beds of packed solids with heat flowing through the container wall into a fluid flowing through the bed. It presents an analytical treatment and includes also design procedures based thereupon.

The analysis is based upon four simultaneous mechanisms for heat flow. These are a convective transport of heat due to net flow of the fluid, a conductive process through the solid particles, a heat flow between fluid and particles through a film resistance and a conductive process through the fluid phase. The latter mechanism consists of the sum of molecular thermal conductivity and the turbulent diffusivity of the fluid. In many industrial applications the turbulent diffusivity is the predominant mechanism among the conductive processes.

The mechanisms lead to differential equations which have been solved for cylindrical beds. Point solutions for solids and fluid temperature are presented and solutions are given as well in terms of mixed terminal fluid temperatures. Equations have been set up for the following circumstances: (1) Fixed bed heat exchangers, (2) Moving bed heat exchangers, and (3) Fixed bed chemical reactors.

The solution for packed heat exchangers has been checked satisfactorily for particles of low conductivity with experimental data from the literature as well as from the Princeton laboratory using independently determined values of turbulent diffusivity. The contribution of solids of high thermal conductivity is evaluated through new data with metal spheres. Use of the derived equations for design and the source of the physical parameters is outlined in the final section of the paper. Illustrative problems are solved.

THE initial heat-transfer studies by Colburn (*3*), which were extended recently by Leva (*14, 15, 16*) give the major experimental results extant in the field. Both authors correlated their results empirically through the use of dimensional analysis. Attempts by others (*1, 4, 5, 9, 10, 21, 23*) to treat the problem analytically on the basis of component mechanisms have been handicapped by a lack in the literature of quantitative knowledge concerning individual mechanisms. Only relatively recently have data in this regard been forthcoming. For example, Wilke and Hougen (*24*) and Hurt (*12*) have reported on heat-transfer coefficients between solid and gas in packed beds. Also Bernard and Wilhelm (*2*) studied turbulent diffusion coefficients in packed beds. Heat transfer by turbulent exchange in the fluid between particles is believed to be the predominant mechanism in many industrial applications at temperature levels in which radiation may be excluded. The present work was a parallel study to the turbulent eddy diffusion measurements mentioned above and is a first direct application of these measurements.

Heat transfer in packed beds with a flowing fluid is encountered industrially in the design and operation of steady-state packed heat exchangers, superheaters and catalytic reactors. This paper is devoted primarily to heat exchangers although a solution including a chemical reaction also is presented. By the addition of appropriate terms in the basic equations and their solutions, moving bed arrangements such as pebble heaters, or nonsteady state processes such as adsorbers or roasting kilns may also be treated by the procedures given.

Heat Balance Differential Equations

In what follows it will be assumed that the flow of heat within a mass of granular material may occur by means of five distinct procedures. Heat flow may occur in the fluid phase by conductive processes under a fluid temperature gradient. Heat may also be transmitted within solid particles and from one particle to the next through a film resistance between the particles. The flow through this complex path results primarily from gradients in solid temperature. Concurrently with these two mechanisms there is an interchange of heat between the two phases which is activated by a temperature difference between particle and fluid. The fourth and fifth modes of heat flow are the result of net flow of solid and fluid through temperature gradients established in the system.

The following vector equations express the steady-state heat balances for the various transfer mechanisms. For generality they include heat generation by chemical reaction as well.

$$div(-K_f grad.t_f) + div(-K_s grad.t_s) + div(CG't_f) + div(C_s S't_s) + R^{\circ}\Delta H = 0 \qquad (1)$$

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TABLE 1

Investigator	Terms Used	Treatment of Data
Damköhler (4-5)	I = III	Analytical solution applied to Colburn (3) data to obtain K_f.
Wilhelm, Johnson and Acton (21)	I = II + IV IV + II = VII	Analytical solution carried out step-wise in the axial direction.
Grossmann (9)	I = II + IV IV + II = VII	Graphical solution.
Hall and Smith (10)	I = II + IV IV + II = VII	Graphical solution using temperature measurements in bed with no reaction to determine K_e, then Grossmann's method applied to their data with reaction.
Arthur and Linnett (1)	I = III + IV + VI IV + VI = VII	Analytical solution applied to their data to determine h_v, E_r, E_f by a graphical treatment of data.
Wilhelm, Johnson, Wynkoop and Collier (22)	I = II + IV IV + II = VII	Electrical network solution carried out step-wise in the axial direction.
Present Solution	I = II + III + IV II + IV = VII	Analytical solution for no reaction applied to data of Colburn (3), Leva (14-16) and that of present authors to get E_f, K_e. Also analytical solution for reaction and case for no reaction but including solids flow.

$$div(-K_e grad.t_s) + h_v(t_s - t_f) + R^*\Delta H + div(C_p S' t_s) = 0 \quad (2)$$

There are two temperature variables, temperature of the solid, t_s, and temperature of the fluid, t_f. Hence the need for two equations for solution. Equation (1) is a heat balance for all the material, solid and fluid, in a given differential volume; while Equation (2) is a heat balance on the solids alone. The meaning of each term and sources of the physical constants are given as follows:

$div(-K_f grad.t_f)$ represents the difference in heat flow into and out of a unit volume per unit time by means of conduction in the fluid phase and in the direction of maximum decreasing temperature gradient in that phase. The effective fluid conductivity, K_f is the sum of two conductivities, the ordinary fluid molecular conductivity and a contribution due to turbulence within the bed. Stated formally:

$$K_f = \epsilon k_f + C\rho E \quad (3)$$

where k_f, the molecular conductivity, C, fluid heat capacity and ρ, the fluid density are readily available or estimatable physical properties. ϵ, the fraction void between particles is measurable. E, the turbulent eddy diffusivity was measured directly in packed beds of spheres, cylinders, cubes and granules by Bernard and Wilhelm (2) and is available for a wide range of modified Reynolds numbers.

$div(-K_e grad.t_s)$ is the difference in the heat flow into and out of a unit volume of bed per unit time by means of conduction through one solid-phase particle to the next and in the direction of maximum decreasing temperature gradient in the solid path. K_e is the conductivity of a complex path including both phases. It represents the heat flow within solid particles and from particle to particle through a thermal resistance which includes a path through the fluid fillet in the zone of contact and another through the contact point itself. (*See* Fig. 12.) It may be anticipated that the value of K_e depends upon the thermal conductivities of solid and fluid. K_e may also be expected to depend somewhat on the Reynolds number for flow through the bed because of an effect upon the effective thermal resistance of the contact-point fluid path. K_e has not been reported in the literature as an independently measured parameter. It is the only parameter in Equations (1) and (2) to which numerical values may not be assigned from independent sources. Values of K_e may be evaluated, however, through an analysis of heat-transfer data using Equations (1) and (2). This has been done and is reported later in the paper. As a result, it has been found that K_e is unimportant for low conducting solids such as glass, porcelain and porous catalyst carriers compared to K_f, the effective conductivity of the fluid path. K_e may not be neglected for highly conducting particles such as steel or lead in which case it is also dependent upon Reynolds number.

$div(CG't_f)$ is the difference in heat flow into and out of a unit volume of packed bed per unit time because of the convective transport of heat by means of the mass flow of fluid, G', through the established fluid temperature gradient. The parallel term, $div(C_p S' t_s)$ represents a similar heat-transport mechanism because of the movement of solid particles, S', through a solid temperature gradient.

$-R^*\Delta H$ is the rate of heat generation in a unit volume of bed because of chemical reaction. The rate of reaction, R^*, will depend upon catalyst activity, catalyst temperature and reactant concentration. ΔH is the heat of reaction.

The final term to be identified, $h_v(t_s - t_f)$, is the rate of heat transport per unit volume and time from solid particles to the fluid phase. The driving force is the temperature difference between the phases. h_v is a volumetric film coefficient which is independently available for spheres, cylinders and granules for a wide range of gas flows from the studies of Wilke and Hougen (24), Gamson, Thodos and Hougen (7) and Hurt (12). McCune and Wilhelm (19) measured k_L for fixed beds with water as the fluid and with spherical and granular particles. They showed the mass-heat transfer analogy to hold permitting the data to be applied to heat transfer between solids and liquids. (For a schematic picture of the mechanisms here proposed, *see* Fig. 12.)

Most heat-transfer applications are for cylindrical reactor shapes and Equations (1) and (2) will therefore be expressed in terms of the cylindrical coordinates, radius, r, axial distance, x, and angular position, ϕ. At the same time the case will be limited to a fixed bed, all terms containing S' being excluded. An analysis of the moving bed case is reserved for a later section.

$$C\left[\frac{1}{r}\frac{\delta}{\delta r}(rt_f G_r) + \frac{\delta(t_f G_x)}{\delta x} + \frac{1}{r}\frac{\delta(t_f G_\phi)}{\delta \phi}\right] + R^*\Delta H - K_f\left[\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta t_f}{\delta r}\right) + \frac{\delta^2 t_f}{\delta x^2} + \frac{1}{r^2}\frac{\delta^2 t_f}{\delta \phi^2}\right] - K_e\left[\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta t_s}{\delta r}\right) + \frac{\delta^2 t_s}{\delta x^2} + \frac{1}{r^2}\frac{\delta^2 t_s}{\delta \phi^2}\right] = 0 \quad (4)$$

$$+R^*\Delta H - K_s\left[\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta t_s}{\delta r}\right) + \frac{\delta^2 t_s}{\delta x^2} + \frac{1}{r^2}\frac{\delta^2 t_s}{\delta \phi^2}\right] + h_v(t_s - t_f) = 0 \quad (5)$$

It can safely be assumed that for a particle which is small compared to the vessel, G_r is constant radially and equal to G_w. Also

$$G_r = G_\phi = 0$$

and

$$\frac{\delta t_r}{\delta \phi} = \frac{\delta t_s}{\delta \phi} = 0.$$

Hence:

$$CG_x\frac{\delta t_f}{\delta x} + R^*\Delta H - K_f\left[\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta t_f}{\delta r}\right) + \frac{1}{r^2}\frac{\delta^2 t_f}{\delta x^2}\right] - K_e\left[\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta t_s}{\delta r}\right) + \frac{1}{r^2}\frac{\delta^2 t_s}{\delta x^2}\right] = 0 \quad (6)$$

$$+R^*\Delta H - K_s\left[\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta t_s}{\delta r}\right) + \frac{1}{r^2}\frac{\delta^2 t_s}{\delta x^2}\right] + h_v(t_s - t_f) = 0 \quad (7)$$

Integrating Equations (6) and (7) radially for a cylindrical slice of thickness dx, Equations (8) and (9) are obtained.

$$K_s r \frac{\delta t_s}{\delta r} - h_v \int_o^r r(t_s - t_f)dr = 0 \tag{11}$$

$$\int_o^r (2\pi r dx) G_o C \frac{\delta t_f}{\delta x} dr + \int_o^r (2\pi r dx) R^* \Delta H dr - (2\pi r dx) K_f \frac{\delta t_f}{\delta r}$$

$$\text{I} \qquad \text{II} \qquad \text{III}$$

$$- (2\pi r dx) K_s \frac{\delta t_s}{\delta r} - \int_o^r \frac{2\pi K_f dx}{r} \frac{\delta^2 t_f}{\delta x^2} dr - \int_o^r \frac{2\pi K_s dx}{r} \frac{\delta^2 t_s}{\delta x^2} dr = 0 \tag{8}$$

$$\text{IV} \qquad \text{V} \qquad \text{VI}$$

$$+ \int_o^r (2\pi r dx) R^{\frac{1}{2}} \Delta H dr - (2\pi r dx) K_s \frac{\delta t_s}{\delta r} - \int_o^r \frac{2\pi K_s dx}{r} \frac{\delta^2 t_s}{\delta x^2} dr$$

$$\text{II} \qquad \text{IV} \qquad \text{VI}$$

$$+ \int_o^r (2\pi r dx) h_v (t_s - t_f) dr = 0 \tag{9}$$

$$\text{VII}$$

The general differential equations shown have been used implicitly in a number of previous investigations with several simplifying assumptions in each case. Because of the complexity of the solutions to the complete equations it has been found necessary to eliminate certain terms. The choice of terms to be eliminated must be governed initially by the common values for those terms and their importance with respect to other terms. However, in the last analysis a proper judgment is based on the accuracy with which the residue equations predict the performance of different heat-transfer units over a wide range of conditions. Also, since it is necessary to use values of certain physical constants, viz., $R^*\Delta H$, $K_f = \epsilon k_f + C\rho E$, K_s, and h_v to satisfy the measured values of temperatures, a second test of assumptions regarding the dropping of terms is whether the physical constants enumerated agree with corresponding values when measured independently.

Table 1 presents a brief summary of the various combinations of terms in Equations (8) and (9) that were used in solutions by previous investigators and in the present work.

Solution Without Chemical Reaction or Flow of Solids. The assumptions for the solution are as follows:

(1) G_o, C, K_f, K_s, h_v are constant within the confines of the reactor.
(2) Axial conductive heat flow terms are negligible compared to the other terms.

These assumptions applied to Equations (8) and (9) lead to:

$$G_o C \int_o^r r \frac{\delta t_f}{\delta x} dr - K_f r \frac{\delta t_f}{\delta r} - K_s r \frac{\delta t_s}{\delta r} = 0 \tag{10}$$

Consider cases in which the following boundary conditions apply:

$0 < r < R_T \quad x = 0 \quad t_f = t_{ent}$

$0 < x < L \quad r = R_T \quad t_s = t_w$

Let:

$$t_s = u_o(x) + \sum_{n=1}^{\infty} u_n(x) J_o(a_n r) \tag{12}$$

$$t_f = v_o(x) + \sum_{n=1}^{\infty} v_n(x) J_o(a_n r)$$

where the u_n's and v_n's are functions of x which are yet to be determined and the a_n's are constants also to be determined. From the boundary conditions (12):

$$(t_s)_{R_T} = u_o(x) + \Sigma u_n(x) J_o(a_n R_T) = t_w$$

One can set:

$$u_o(x) = t_w \text{ and } J_o(a_n R_T) = 0$$

whence

$$a_n = \frac{\rho_n}{R_T} \tag{13}$$

where ρ_n is the n'th root of $J_o(\rho) = 0$.

Also from the boundary conditions (12):

$$(t_f)_{x=o} = t_{ent} = v_o(0) + \Sigma v_n(0) J_o(a_n r) \tag{14}$$

The constant, $t_{ent} - v_o(0)$, can be expanded in a Bessel series:

$$t_{ent} - v_o(0) = \Sigma A_r J_o(k_r r) \tag{15}$$

where k_r are the roots of $J_o(k) = 0$. By comparing (14) and (15) it is seen that the terms after the summation sign in (14) are equal, term by term to those in (15) and from reference (*20*):

$$A_r = v_n(0) = \frac{2\int_o^1 y[t_{ent} - v_o(0)] J_o(\rho_n y) dy}{[J_1(a_n R_T)]^2} \tag{16}$$

where

$$y = \frac{r}{R_T}$$

Therefore:

$$v_n(0) = A_r = \frac{2[t_{ent} - v_o(0)]}{\rho_n J_1(\rho_n)} \tag{17}$$

Substituting (12) into (11):

$$-K_s r \Sigma u_n a_n J_1(a_n r) - h_v \int_o^r [(u_o - v_o) + \Sigma(u_n - v_n) J_o(a_n r)] r dr = 0 \tag{18}$$

or

$$-K_s r \Sigma u_n a_n J_1(a_n r) - \frac{h_v r^2}{2}(u_o - v_o) + h_v \Sigma(u_n - v_n) \frac{r}{a_n} J_1(a_n r) = 0$$

Equating coefficients of like terms in J_1 the following relationships can be arrived at for u_n and v_n:

$$u_o = v_o = t_w \text{ (Recalling (13))} \tag{19}$$

$$u_n = \frac{h_v}{h_v + K_s a_n^2} v_n \tag{20}$$

Substituting (12) in (10):

$$\frac{G_o C v_n' r}{a_n} J_1(a_n r) + K_s r \Sigma u_n a_n J_1(a_n r) + K_f r \Sigma v_n a_n J_1(a_n r) = 0 \tag{21}$$

Equating coefficients of like terms in J_1 the further relationships for u_n and v_n can be found:

$$K_s u_n a_n + K_f v_n a_n = \frac{-G_o C v_n'}{a_n} \tag{22}$$

Combining (20) and (22):

$$\frac{v_n'}{v_n} = -\frac{a_n^2(h_v K_s + h_v K_f + K_f K_s a_n^2)}{G_o C(h_v + K_s a_n^2)} \tag{23}$$

Integrating:

$$v_n(x) = v_n(0) \exp\left[\frac{-a_n^2 x(h_v K_s + h_v K_f + K_f K_s a_n^2)}{G_o C(h_v + K_s a_n^2)}\right] \tag{24}$$

These values can now be substituted for v_n from (17), (19) and (24) in the expression for the fluid temperature at any position in the bed, t_f, to get

$$t_f = t_w + \sum \frac{2(t_{out} - t_w)}{\rho_n J_1(\rho_n)} J_0(a_n r) \exp\left[\frac{-a_n^2 x (h_c K_o + h_c K_f + K_f K_o a_n^2)}{G_o C (h_c + K_o a_n^2)}\right] \quad (25)$$

By definition $(t_{out} - t_w) = -\Delta t_{out}$; from (13)

$$a_n = \frac{\rho_n}{R_T}$$

from (3) $K_f = \epsilon k_f + C\rho E$. Defining the dimensionless groups—

$$R\acute{e} = \frac{D_p G_o}{\mu}, \quad Pr = \frac{C\mu}{k_f}, \quad P\acute{e} = \frac{D_p V}{E}$$

and

$$S_n = \frac{2}{3} \rho_n^2 \frac{Pr\%}{J_H(1-\epsilon)} \left(\frac{D_p}{D_T}\right)^2$$

Table 2 showing pertinent mathematical constants was constructed using the Jahnke-Emde Tables (*13*).

These relations, groups and constants can now be substituted in (25) to get:

$$\begin{aligned} t_f = t_w &- 1.602\Delta t_{out} J_o\left(2.405 \frac{r}{R_T}\right) \exp\left[-23.14\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_1} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ &+ 1.065\Delta t_{out} J_o\left(5.52 \frac{r}{R_T}\right) \exp\left[-121.9\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_2} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ &- 0.851\Delta t_{out} J_o\left(8.65 \frac{r}{R_T}\right) \exp\left[-299.6\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_3} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ &+ 0.729\Delta t_{out} J_o\left(11.79 \frac{r}{R_T}\right) \exp\left[-556\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_4} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ &+ \ldots \end{aligned} \quad (26)$$

A similar treatment of Equation (12) for t_n and (20) gives a point solution for solids temperatures anywhere within the bed. In practice, it is difficult to obtain reliable values of point temperatures of fluid or solid. It is usually more convenient and useful to have an expression for the mean temperature of the fluid leaving the bed, where $x = L$.

Then:

$$t_{ex} = \frac{2\pi \int_0^{R_T} r t_f dr}{\pi R_T^2}$$

$$= t_w - \sum \frac{4\Delta t_{out}}{\rho_n^2} \exp\left[-4\rho_n^2\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_n} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \quad (27)$$

Recalling that $\Delta t_{ex} = t_w - t_{ex}$:

$$\begin{aligned} \frac{\Delta t_{ex}}{\Delta t_{out}} = 0.692 &\exp\left[-23.14\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_1} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ + 0.1313 &\exp\left[-121.9\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_2} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ + 0.0534 &\exp\left[-299.6\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_3} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ + 0.0288 &\exp\left[-556\left(\frac{1}{R\acute{e}\dfrac{C\mu}{K_o} + S_4} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \\ + &\ldots \end{aligned} \quad (28)$$

It is convenient also to have available an expression for the heat-transfer coefficient for the flow of heat from the wall to the fluid in terms of the tube area because experimental data are frequently in this form. The ordinary wall-film heat-transfer coefficient is as follows:

$$\begin{aligned} h_w &= \frac{q}{A_T \Delta t_{lm}} \\ &= \frac{(t_{ex} - t_{out})(G_o C)(0.785 D_T^2)}{\pi L D_T \Delta t_{lm}} \\ &= \frac{G_o C D_T}{4L} \ln \frac{\Delta t_{out}}{\Delta t_{ex}} \end{aligned} \quad (29)$$

A direct substitution of the ratios of Δt's from (28) into (29) will yield the desired alternate solution.

It is well at this point to review the physical meaning of the various rate terms in the exponents of Equation (28).

$R\acute{e}\frac{C\mu}{K_o}$ represents the path of conduction governed by temperature gradients in the solid path.

$$S_n = \frac{2}{3} \frac{(\rho_n)^2 Pr\%}{J_H(1-\epsilon)} \left(\frac{D_p}{D_T}\right)^2$$

represents the transfer path from solid particles to fluid surrounding them. J_H is a dimensionless group through which h_c, the film coefficient, is represented.

$\frac{\epsilon}{R\acute{e}Pr}$ is the contribution of molecular conductivity in the fluid phase.

$\frac{1}{P\acute{e}}$ is the contribution of turbulent thermal diffusivity in the fluid phase.

In certain common cases simplifications may be made in Equation (28). By referring to this equation it may be seen that were it not for the S_n terms all bracketted terms of the exponents would be identical and the Δt ratio would be constant for any particular value of the net variable term in the exponents regardless of specific values of component variables. S_n drops out under two circumstances. The first of these occurs when S_n is small compared to $R\acute{e}C\mu/K_o$. The second case results when the fraction $1/(R\acute{e}C\mu/K_o + S_n)$ is small compared to the sum of gas conductivity fractions, $(\epsilon/R\acute{e}Pr + 1/P\acute{e})$. The latter circumstance is realized when the solid path conductivity is negligibly small. It follows then that the solid-to-gas film resistance, represented by the S_n term, also must be unimportant. Either or both of the above simplifying situations occur frequently. In such cases

$$\frac{\Delta t_{ex}}{\Delta t_{out}} = \theta(P)$$

where

$$P = \left[\frac{1}{Re\,\frac{C_\mu}{K_s}} + \frac{\epsilon}{RePr} + \frac{1}{Pe}\right]\frac{D_p}{D_T}\frac{L}{D_T} = \left[\frac{\epsilon}{RePr} + \frac{1}{Pe}\right]\frac{D_p}{D_T}\frac{L}{D_T}$$

(Case 1) (Case 2)

This functionality has been determined for four terms of the series and the results are tabulated in Table 3 and presented graphically in Figures 1 and 2 for applications over an extremely wide range of circumstances. In most packed-bed heat-exchanger problems, however, the attempt is to have the fluid temperatures approach wall temperatures closely, which means that $\Delta t_{ex}/\Delta t_{ent}$ will have small values. Reference to Table 3 shows that such temperature arrangements permit the utilization of value of P with only one term of the series. For example, for values of $\Delta t_{ex}/\Delta t_{ent}$ less than 0.28, corresponding to P larger than 0.04, a mathematical accuracy of better than one per cent will be obtained. Thus, for cases when $\Delta t_{ex}/\Delta t_{ent} < 0.28$, Equation (28) may be simplified to the following:

$$\frac{\Delta t_{ex}}{\Delta t_{ent}} = 0.692e^{-23.14P} \tag{30}$$

To obtain an equation in terms of a wall-area heat-transfer coefficient, Equation (30) can be substituted into (29) at the same time substituting for the definition of P:

$$h_w = 5.79\,RePr\,\frac{k_f}{D_T}\left[\frac{1}{Re\,\frac{C_\mu}{K_s}} + \frac{\epsilon}{RePr} + \frac{1}{Pe}\right] + 0.0912\,\frac{G_oCD_T}{L} \tag{31}$$

Solution with Chemical Reaction and Without Flow of Solids. The application of a heat balance to include chemical reaction starts with Equations (8) and (9) which are presented in slightly modified form as follows:

$$G_oC\int_o^r r\frac{\delta t_f}{\delta x}dr + \int_o^r rR^*\Delta H dr - K_f r\frac{\delta t_f}{\delta r} - rK_s r\frac{\delta t_s}{\delta r} - K_f\int_o^r \frac{1}{r}\frac{\delta^2 t_f}{\delta x^2}dr - K_s\int_o^r \frac{1}{r}\frac{\delta^2 t_s}{\delta x^2}dr = 0 \tag{8a}$$

$$+\int_o^r R^*\Delta H dr - K_s r\frac{\delta t_s}{\delta r} - K_s\int_o^r \frac{1}{r}\frac{\delta^2 t_s}{\delta x^2}dr + h_v\int_o^r r(t_s - t_f)dr = 0 \tag{9a}$$

R^* may usually be expressed as the product of concentration terms by a reaction rate constant. The reaction rate constant may be represented as a frequency factor times an exponential in T_s:

$$R^* = C_A C_B \cdots A e^{\frac{-E_a}{kT_s}} \tag{32}$$

The assumption in this development is that $R^*\Delta H$ may be expressed as a linear function of solids temperature. It is realized that this is not applicable to cases where large concentration or temperature changes occur; the former is the more usual limitation. When considerable concentration changes occur, it is possible to assume a mean value for the concentrations and choose the straight line best fitting the variation of rate with temperature; at this concentration the line may be described algebraically:

$$-R^*\Delta H = C_o + C_1 t_s \tag{33}$$

A second simplification is, as before, to drop the axial conductive terms, giving:

$$G_oC\int_o^r r\frac{\delta t_f}{\delta x}dr - \int_o^r (C_o + C_1 t_s)rdr - K_f r\frac{\delta t_f}{\delta r} - K_s r\frac{\delta t_s}{\delta r} = 0 \tag{34}$$

$$+h_v\int_o^r (t_s - t_f)rdr - K_s r\frac{\delta t_s}{\delta r} - \int_o^r (C_o + C_1 t_s)rdr = 0 \tag{35}$$

Boundary conditions will be imposed as before:

$$0 < r < R_T \qquad x = 0 \qquad t_f = t_{ent}$$

$$0 < x < L \qquad r = R_T \qquad t_s = t_w$$

and form the same Bessel series for t_s and t_f:

$$t_s = u_o(x) + \Sigma u_n(x)J_o(a_n r)$$

$$t_f = v_o(x) + \Sigma v_n(x)J_o(a_n r) \tag{12}$$

Substituting the t_s boundary condition it is found as before:

$$u_o(x) = t_w \text{ and } a_n = \frac{\beta_n}{R_T} \tag{13}$$

Continuing by a similar procedure, an expression is obtained for the mean exit temperature difference:

$$\Delta t_{ex} = -\frac{\Delta HR^*_w}{h_v} + \frac{\Delta HR^*_w L}{G_oC}\sum \frac{e^{-4\rho_n{}^2 W_n} - 1}{W_n\rho_n{}^4} + 4\Delta HR^*_w\left(\frac{1}{h_v} + \frac{\Delta t_{ent}}{\Delta HR^*_w}\right)\sum \frac{e^{-4\rho_n{}^2 W_n}}{\rho_n{}^2} \tag{36}$$

where $-\Delta HR^*_w$ = rate of heat release at wall temperature $= C_o + C_1 t_w$ and

$$W_n = \left[\frac{1}{Re\,\frac{C_\mu}{K_s - \frac{C_1 D_T{}^2}{4\rho_n{}^2}} + \frac{2\rho_n{}^2 Pr^{\frac{2}{3}}}{3j_M(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2} + \frac{\epsilon}{RePr} + \frac{1}{Pe}\right]\frac{D_p}{D_T}\frac{L}{D_T}$$

W'_n may be compared to the exponents of Equation (28), the solution for no chemical reaction:

$$\left[\frac{1}{Re\,\frac{C_\mu}{K_s} + \frac{2}{3}\rho_n{}^2\,\frac{Pr^{\frac{2}{3}}}{j_M(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2} + \frac{\epsilon}{RePr} + \frac{1}{Pe}\right]\frac{D_p}{D_T}\frac{L}{D_T}$$

Equation (35) may be checked by setting $C_o = C_1 = 0$ and it is found identical to Equation (28) for packed heat exchangers.

For the determination of fraction conversion it is necessary to have values of t_s from $0 < x < L$ and $0 < r < R_T$. The solution is

TABLE 2

n	ρ_n	ρ_n^2	$J_1(\rho_n)$	$\frac{2}{\rho_n J_1(\rho_n)}$	$\frac{4}{\rho_n^2}$	$4\rho_n^2$	$\frac{2}{3\rho_n^2}$
1	2.405	5.784	+0.5191	+1.602	0.6916	23.14	3.856
2	5.520	30.47	−0.3403	−1.065	0.1313	121.9	20.31
3	8.654	74.89	+0.2715	+0.8512	0.05341	299.6	49.9
4	11.793	139.1	−0.2325	−0.7284	0.02876	566	92.7

TABLE 3

P	1st Term	2nd Term Absolute Value	% of Total	3rd Term Absolute Value	% of Total	4th Term Absolute Value	% of Total	$\frac{\Delta t_{out}}{\Delta t_{out}}$
0.0001	0.649	0.130	.....	0.052	....	0.027	3.01	0.898
0.0002	0.649	0.128	.....	0.050	....	0.026	2.91	0.893
0.0004	0.654	0.125	.....	0.048	....	0.024	2.73	0.881
0.001	0.674	0.116	.....	0.041	....	0.017	2.00	0.848
0.002	0.660	0.108	.....	0.030	3.74	0.010	1.24	0.802
0.005	0.616	0.071	10.13	0.012	1.71	0.002	0.29	0.701
0.010	0.549	0.039	6.60	0.003	0.51	.....	....	0.591
0.020	0.436	0.018	3.87	.....	....	.....	....	0.446
0.050	0.218	0.0062	0.09	.....	....	.....	....	0.216
0.100	0.0678	.....	.....	.....	....	.....	....	0.0687
0.200	6.85×10^{-3}	.....	.....	.....	....	.....	....	6.85×10^{-3}
0.300	6.78×10^{-4}	.....	.....	.....	....	.....	....	6.78×10^{-4}
0.400	6.74×10^{-5}	.....	.....	.....	....	.....	....	6.74×10^{-5}

$$t_s = t_w + \sum \frac{h_v}{h_v + K_s\rho_n^2 - C_1}\left\{\frac{\Delta HR^*_w L}{2\rho_n^3 J_1(\rho_n) W_n G_o C}\left(e^{-4\rho_n^2 W_n \frac{x}{L}} - 1\right)\right.$$

$$\left. - \frac{2}{\rho_n J_1(\rho_n)}\left(\frac{\Delta HR^*_w}{h_v} + \Delta t_{out}\right) e^{-4\rho_n^2 W_n \frac{x}{L}}\right\} J_o\left(\rho_n \frac{r}{R}\right) \qquad (37)$$

These values of t_s act on the kinetic expression (33) to give:

$$\int_o^{R_T} \frac{(C_o + C_1 t_s)}{-\Delta H} 2\pi r dr = \pi R_T^2 \frac{G_{A1}}{M_A}\frac{df}{dx} \qquad (38)$$

Substituting (37) in (38) and integrating in the radial direction as indicated and then in the axial direction:

$$\frac{f^2}{2} = \frac{R^*_w M_A L}{G_{A1}}\left\{1 - \frac{C_1 L}{G_o C}\sum \frac{h_v}{h_v + K_s\rho_n^2 - C_1}\frac{1}{\rho_n^4 W_n}\left(1 - \frac{1 - e^{-4\rho_n^2 W_n}}{4\rho_n^2 W_n}\right)\right.$$

$$\left. - C_1\left(\frac{1}{h_v} + \frac{\Delta t_{out}}{\Delta HR^*_w}\right)\sum \frac{h_v}{h_v + K_s\rho_n^2 - C_1}\left(\frac{1 - e^{-4\rho_n^2 W_n}}{\rho_n^4 W_n}\right)\right\} \qquad (39)$$

For those cases where (as will often be the case):

$$K_s\left(\frac{\rho_n}{R_T}\right)^2 << h_v - C_1 \text{ and } K_s - \frac{C_1 D_T^2}{4\rho_n^2} \to 0$$

Equation (39) reduces to:

$$\frac{f^2}{2} = \frac{R^*_w M_A L}{G_{A1}}\left\{1 - \left(\frac{C_1 L}{G_o C}\right)\left(\frac{h_v}{h_v - C_1}\right)\frac{1}{P}\sum\frac{1}{\rho_n^4}\right.$$

$$+ \frac{1}{4}\left(\frac{C_1 L}{G_o C}\right)\left(\frac{h_v}{h_v - C_1}\right)\frac{1}{P^2}\sum\frac{1}{\rho_n^6} - \frac{1}{4}\left(\frac{C_1 L}{G_o C}\right)\left(\frac{h_v}{h_v - C_1}\right)\frac{1}{P^2}\sum\frac{e^{-4\rho_n^2 P}}{\rho_n^6}$$

$$- C_1\left(\frac{1}{h_v} + \frac{\Delta t_{out}}{\Delta HR^*_w}\right)\left(\frac{h_v}{h_v - C_1}\right)\frac{1}{P}\sum\frac{1}{\rho_n^4}$$

$$\left. + C_1\left(\frac{1}{h_v} + \frac{\Delta t_{out}}{\Delta HR^*_w}\right)\left(\frac{h_v}{h_v - C_1}\right)\frac{1}{P}\sum\frac{e^{-4\rho_n^2 P}}{\rho_n^4}\right\} \qquad (40)$$

From Table 2 it is seen that:

$$\sum\frac{1}{\rho_n^4} = 0.03120; \sum\frac{1}{\rho_n^6} = 0.00521 \quad \text{and}$$

If we define

$$M = \sum\frac{e^{-4\rho_n^2 P}}{\rho_n^6}$$

$$N = \sum\frac{e^{-4\rho_n^2 P}}{\rho_n^4}$$

Equation (40) may be written as:

$$\frac{f^2}{2} = \frac{R^*_w M_A L}{G_{A1}}\left\{1 + \left(\frac{C_1 L}{G_o C}\right)\left(\frac{h_v}{h_v - C_1}\right)\left(\frac{0.00521 - M}{4P^2}\right.\right.$$

$$\left.\left. - \frac{0.0312}{P}\right) + C_1\left(\frac{1}{h_v} + \frac{\Delta t_{out}}{\Delta HR^*_w}\right)\left(\frac{h_v}{h_v - C_1}\right)\left(\frac{1}{P}\right)(N - 0.0312)\right\} \qquad (40a)$$

The series represented by M and N as well as those in the more general Equation (39) converge rapidly because of the high powers of ρ_n.

Solution with Solids Flow, No Chemical Reaction. Consider the case of a heat exchanger with both solids and fluid in circulation. This type of apparatus is important where solids are to be heated or cooled in a fluidized state. It will be assumed that the wall of the tube is at a constant temperature. The solids and fluid are introduced each at its own temperature but with initially no radial temperature gradient. Flow may be cocurrent or countercurrent. The same assumptions will be made regarding the constancy of G_o, C, K_f, K_s, h_v with the added assumption of the constancy of S_o, the mass velocity of solids. Axial conductive terms are neglected as before.

Equations (1) and (2) for this case will have only the $R^*\Delta H$ terms deleted. When they are expressed in cylindrical coordinates the following equations are obtained:

$$K_s r\frac{\delta t_s}{\delta r} + K_f r\frac{\delta t_f}{\delta r} - CG_o\int_o^r r\frac{\delta t_f}{\delta x}dr$$

$$- C_o S_o\int_o^r r\frac{\delta t_s}{\delta x}dr = 0 \qquad (41)$$

$$K_s r\frac{\delta t_s}{\delta r} - h_v\int_o^r r(t_s - t_f)dr$$

$$- C_o S_o\int_o^r r\frac{\delta t_s}{\delta x}dr = 0 \qquad (42)$$

Boundary conditions are:

$$0 < x < L \quad r = R_T \quad t_s = t_f = t_w$$

$$0 < r < R_T \quad x = L \quad t_f = t_{feed}$$

$$0 < r < R_T \quad x = 0 \quad t_s = t_{sent} \qquad (43)$$

G_o and S_o will have the same signs for cocurrent flow and opposite for countercurrent flow.

The same Bessel-Fourier series may be formed as given in Equations (12). When the boundary conditions and the differential equations are applied to these series point, solutions for solids and fluid temperature are obtained. The differential equations are of the second order, however, and it is possible to have three types of solution depending upon the relative values of the parameters. Rate

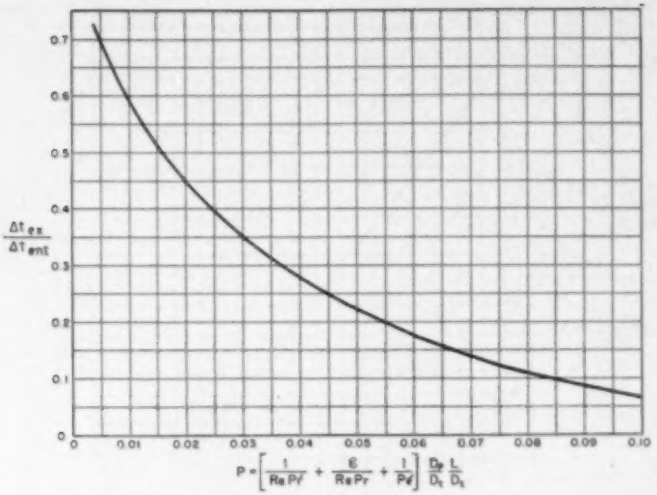

Fig. 1. Plot of Equation 25 for Poor Conductors and/or Small Values of D_p/D_T

functions similar to the P function in the static bed-exchanger solution or the W function in the static bed-reactor solution are obtained. There are two of these rate functions, however, which we shall call Q_a and T_a and define as:

$$Q_a, T_a = -\frac{L}{2}\left[\left(\frac{K_f\rho_a^2}{CG_o} + \frac{K_s\rho_a^2}{C_sS_o} + \frac{h_v}{CG_o} + \frac{h_v}{C_sS_o}\right)\right] \pm \sqrt{\left[\left(\frac{K_f\rho_a^2}{CG_o} - \frac{K_s\rho_a^2}{C_sS_o}\right) + \left(\frac{h_v}{CG_o} - \frac{h_v}{C_sS_o}\right)\right]^2 + 4\frac{h_v}{CG_o}\frac{h_v}{C_sS_o}} \tag{44}$$

In terms of the groups which have been used in the previous solutions:

$$Q_a, T_a = -2\rho_a^2\left\{\frac{\epsilon}{Re Pr} + \frac{1}{Pe} + \frac{K_s}{C_sS_oD_p} + \frac{3(1-\epsilon)j_H}{2\rho_a^2 Pr^{2/3}}\left(\frac{D_T}{D_p}\right)^2\left(1 + \frac{CG_o}{C_sS_o}\right) \pm \sqrt{\left[\frac{\epsilon}{Re Pr} + \frac{1}{Pe} - \frac{K_s}{C_sS_oD_p} + \frac{3(1-\epsilon)j_H}{2\rho_a^2 Pr^{2/3}}\left(\frac{D_T}{D_p}\right)^2\left(1 - \frac{CG_o}{C_sS_o}\right)\right]^2 + 4\left[\frac{3(1-\epsilon)j_H}{2\rho_a^2 Pr^{2/3}}\right]^2\frac{CG_o}{C_sS_o}}\right\} \tag{45}$$

When the values of Q_a, T_a are real, as will most often occur, the solution for the mean temperature of the fluid and solid at their respective exit points will be:

$$\Delta t_{fex} = \sum \frac{4}{\rho_a^2}\frac{(e^{-Q_a} - e^{-T_a})\Delta t_{fent} + \frac{C_sS_o}{h_vL}e^{-(T_a+Q_a)}(T_a - Q_a)\Delta t_{sent}}{\left[\left(\frac{K_f\rho_a^2}{h_v} + 1\right) - \frac{C_sS_o}{h_vL}T_a\right]e^{-T_a} - \left[\left(\frac{K_s\rho_a^2}{h_v} + 1\right) - \frac{C_sS_o}{h_vL}Q_a\right]e^{-Q_a}} \tag{46}$$

$$\Delta t_{fex} = \sum \frac{4}{\rho_a^2}\frac{(e^{-Q_a} - e^{-T_a})\Delta t_{fent} + \frac{CG_o}{h_vL}e^{-(T_a+Q_a)}(T_a - Q_a)\Delta t_{fent}}{\left[\left(\frac{K_f\rho_a^2}{h_v} + 1\right) - \frac{CG_o}{h_vL}T_a\right]e^{-T_a} - \left[\left(\frac{K_f\rho_a^2}{h_v} + 1\right) - \frac{CG_o}{h_vL}Q_a\right]e^{-Q_a}} \tag{47}$$

Verification of Derived Equations for No Chemical Reactions, No Solids Flow

To test the deductive solution presented in this paper for heat transfer in packed beds the experimental data of Colburn (*3*) and Leva (*14-16*) will be employed for materials of low solids conductivity which include catalyst carriers, porcelain and glass in approximately spherical shapes. Solids of high conductivity will be represented by heat-transfer data with steel ball bearings and lead shot obtained in this laboratory and with lead shot measured by Leva (*15*).

First, the present analytical solution for heat transfer will be compared with the empirical formulas of Colburn and Leva which were developed inductively through the use of dimensional analysis applied to data. These data were for materials of low thermal conductivity. Then, because K_s, the effective solids conductivity, is the only parameter not capable of independent experimental measurement further consideration of the subject is based upon a comparison of cases in which K_s is negligibly small with those in which K_s is appreciable. The first case is represented by data with the low conductivity solids listed above and the latter, by data with steel balls and lead shot.

Comparison of Inductive and Deductive Equations. Deductive Equation (31) may be compared with the following empirical equation of Colburn:

$$h_w = 0.011 Re^{0.8} Pr \frac{k_f}{D_p} f\left(\frac{D_p}{D_T}\right) \tag{40}$$

Leva's empirical formula for heating a fluid is:

$$h_w = 0.813 Re^{0.9} \frac{k_f}{D_T} e^{-6D_p/D_T} \tag{41}$$

and for cooling a fluid is:

$$h_w = 3.50 Re^{0.7} \frac{k_f}{D_T} e^{-4.6D_p/D_T} \tag{42}$$

The general parallelism is apparent. Since the final term of (31) provides only a small contribution, either Pe and/or

$$\frac{1}{Re\,\frac{C_p}{K_s} + S_1}$$

must have a strong dependence on $\frac{D_p}{D_T}$ to account for the $f\left(\frac{D_p}{D_T}\right)$ term in Colburn's formula and the exponentials in

$\frac{D_p}{D_T}$ in Leva's formulas.

Case 1: Low Conductivity Solids

The following are the steps employed in this section for relating derived equations and experimental data. First, applying Equations (28) and/or Equation (31) to the heat exchanger data for low conductivity solids of Colburn, Leva and data from this laboratory, values have been computed of Pe' for eddy heat transfer. This is a desirable procedure because of the independent availability of comparable values from mass-diffusion experiments. Evidence is given for the validity of the analysis by demonstrating that these Pe' groups as here determined form a consistent set. The second step is a presentation and discussion of modified Peclet groups for heat transfer from the above experiments. The third and final step deals with a comparison between Pe' from heat transfer and mass transfer sources.

Inspection of Equations (28) or (31) shows that there are three mechanism parameters. $a/Re'Pr$ for molecular conductivity is obtainable directly from the literature. On the basis of a preliminary analysis, the solids conductivity path, $1/Re'C_\mu/K_s$, was assumed negligibly small because no differentiation was found among experiments with glass, celite, gravel, porcelain and clay although a considerable difference in true solids conductivity is represented in this group. As will be shown, this assumption regarding the solids conduction path also leads to complete consistency between the remaining path, that for eddy transfer, Pe', and corresponding values for mass transfer. With these considerations in mind values of Pe' were computed from heat-exchange data. Original data points were used in many instances; in others, to avoid crowding final curves, points were taken from the best lines through original data.

Since it is known that Pe' depends upon Re' and D_p/D_t, a proof of the validity of the analysis would be to show that Pe', determined by means of this analysis applied to the data, does *not* depend upon such variables as L, D_t, D_p or L/D_t. Figures 3 and 4, which are plots of Pe' vs. Re', each for a narrow range of D_p/D_t, show that Pe' is in fact independent of the listed variables. An alternate conclusion is that the solid to fluid thermal resistance at the container wall is not markedly different from that in the main body of the bed. Were there such a difference Pe' determined in this fashion would be a function of tube diameter.

Results of calculations are presented as Pe' vs. Re' in Figures 5, 6, and 7. Figures 5 and 6 give data by Colburn (*3*) and Leva (*14-16*) and Figure 7 data from this

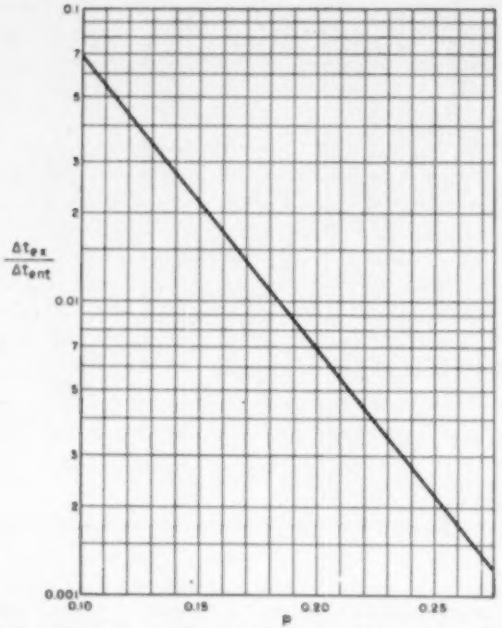

Fig. 2. Plot of Equation 28 for Poor Conductors and/or Small Values of D_p/D_T.

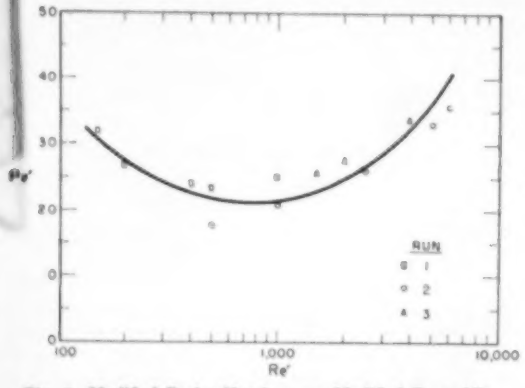

Fig. 3. Modified Peclet Numbers vs. Modified Reynold's Numbers for Constant D_p/D_T Obtained from Packed Heat Exchanger.

Data: Gas flowing downward while being heated.

Run	$\frac{D_s}{D_T}$	D_p in.	D_T in.	L in.	$\frac{L}{D_T}$	Source
1	0.110	0.228	2.1	36	17.2	(*14*)
2	0.121	0.375	3.1	45.5	14.7	(*3*)
3	0.136	0.188	1.4	18	12.9	(*3*)

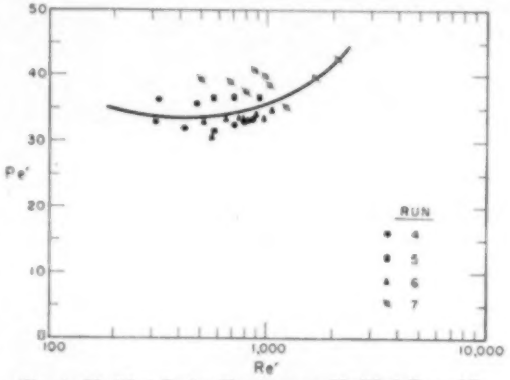

Fig. 4. Modified Peclet Numbers vs. Modified Reynold's Numbers for Constant D_p/D_T Obtained from Packed Heat Exchanger.

Data: Gas flowing downward while being heated.

Run	$\frac{D_s}{D_T}$	D_p in.	D_T in.	L in.	$\frac{L}{D_T}$	Source
4	0.202	0.126	0.6	11	17.7	(*15*)
5	0.205	0.169	0.8	14	17.0	(*15*)
6	0.207	0.170	0.8	14	17.0	(*15*)
7	0.209	0.133	0.6	11	17.7	(*15*)

investigation. Keys with regard to conditions of the experiments are supplied in Table 4. All results in Figure 5, except for a D_p/D_t of 0.22, were computed from best lines through original data. Figures 6 and 7 represent original data. Table 5 presents original data and computed results for the new experiments obtained in this laboratory for two sizes of Socony-Vacuum Co. bead catalyst as the heat-exchanger packing. The apparatus was similar to that of Colburn and Leva. Air was the flowing stream and heat was supplied by condensing steam.

The following broad observations may be made with regard to curve characteristics of Figures 5-7. Concave upward curves are obtained which become quite flat as smaller values of D_p/D_t are considered. The effect of the variable, D_p/D_t, in moving curves vertically becomes smaller and smaller as the ratio of D_p to D_t decreases. This point is shown in Figure 8, which is a cross-plot of Figures 5 and 7 for experiments with gas being heated. That Figure 8 should lead to a high value of Pe' for large values of D_p/D_t may be demonstrated by a reduction of Equation (31) to the limit when D_p/D_t is one. Admittedly this is an hypothetical situation but it expresses the likely condition that as packing size becomes larger, the system approaches the characteristics of an empty tube. Therefore if the heat-transfer data of McAdams (*25*) are taken for an empty tube and $D_p/D_t = 1$ as a limit, the Pe' group is computed to have a value of the order of 300-400 for Re' of 1000.

A frame of reference for the present heat analysis is provided by the eddy mass diffusion measurements of Bernard and Wilhelm (*2*). The method of experiment was the injection and measurement of radial diffusion of a dyestuff solution in a water stream and a carbon dioxide gas in an air stream within beds of solids. Values of the eddy diffusivity, E, and the corresponding modified Peclet group, Pe', differed only by about 15% between the water and gas systems. It was found that above a Re', specific for each D_p/D_t, the Pe' was essentially constant with increasing Re'. However, it was observed that at higher D_p/D_t the curves rose slightly with change in Re'. Below the critical Re, the Pe' dipped first and then rose sharply, a condition that was associated with tube-generated turbulence as opposed to particle generated turbulence at large Re'. In the region below the

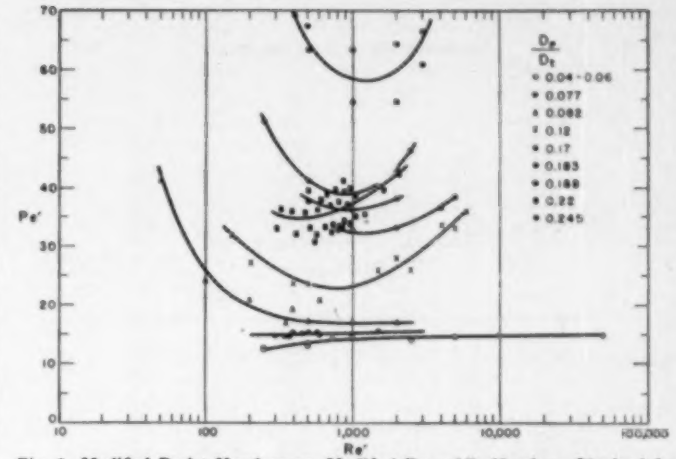

Fig. 5. Modified Peclet Numbers vs. Modified Reynold's Numbers Obtained from Packed Heat Exchanger Data: Gas flowing downward while being heated (*3, 14, 15*)

Table 4

$\frac{D_p}{D_t}$ Groupings Designated in Figures 3,4,5	Experimental D_p/D_t	D_p in.	D_t in.	L in.	Materials*	Investigator	Ref.
		Downflow		Heating			
0.04-0.06	0.04	0.125	3.1	44.5	catalyst carrier gran.		
	0.06	0.187	3.1	44.5	catalyst pellets	Colburn	(3)
0.077	0.077	0.159	2.1	36	Alcoxite pellets	Leva	(15)
	0.0817	0.250	3.1	44.5	catalyst carrier gran.	Colb.(3)	
0.082	0.0812	0.172	2.1	36	glass beads	Leva	(14)
	0.1103	0.228	2.1	36	glass beads	Leva	(14)
0.12	0.121	0.375	3.1	44.5	catalyst carrier pell.	Colb.(3)	
	0.136	0.1875	1.4	18	catalyst carrier	"	"
0.183	0.183	0.562	3.1	44.5	pebbles	Colburn	(3)
0.188	0.188	0.388	2.1	36	glass beads	Leva	(14)
	0.202	0.126	0.6	11	glass beads	"	"
	0.205	0.169	0.8	14	glass beads	"	(15)
0.21	0.209	0.170	0.6	11	glass beads (Note 1)	"	(14)
	0.207	0.170	0.8	14	Alcoxite pellets	"	(15)
	0.228	0.142	0.6	11	glass beads	"	(14)
0.245	0.245	0.508	2.1	36	porcelain balls (Note 2)	"	(14)
		Downflow		Cooling			
0.082	0.082	0.169	2.1	36	glass beads	Leva	
0.11	0.110	0.228	2.1	36	" "	"	
0.16	0.159	0.111	0.8	14	" "	"	
0.1875	0.1875	0.388	2.1	36	" "	"	(16)
	0.205	0.169	0.8	9.1	" "	"	
0.205	0.205	0.169	0.8	14	" "	"	
	0.205	0.169	0.8	12.1	" " (Note 3)	"	
		Upflow		Heating			
0.0236	0.0236	0.089	3.8	36	Socony catalyst beads	(Singer and	
0.0487	0.0487	0.184	3.8	36	" "	"	(Wilhelm

*All runs were for air as the flowing fluid, except: (1) Half of data for air, half for N_2. (2) Half of data for air, half for CO_2; (3) All of data for CO_2.

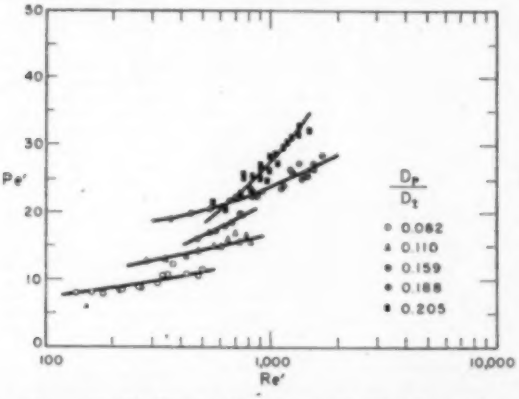

Fig. 6. Modified Peclet Numbers vs. Modified Reynold's Numbers. Obtained from Packed Exchanger Data: Gas flowing downward while being cooled (*16*).

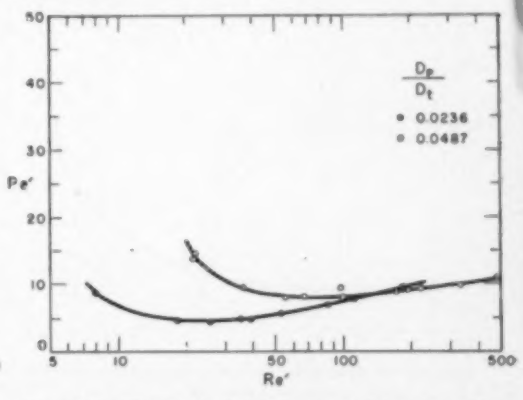

Fig. 7. Modified Peclet Numbers vs. Modified Reynold's Numbers from Packed Exchanger Data: Gas flowing upward while being heated. (Present work.)

Table 5

Heat Transfer Data for Packed Bed Catalyst

D_p = 0.0835"	D_T = 3.79"	L = 36"			= 0.34, 0.37	
G lb/ft² hr.	Re'	t_{out} °F.	t_{in} °F.	t_w °F.	$\frac{\Delta t_{in}}{\Delta t_{out}}$	Pe'
90.7	7.95	76.0	207.1	271.0	0.1285	8.73
120	10.1	76.5	210.1	272.1	0.2170	4.70
160	13.6	79.0	211.6	272.1	0.2108	4.51
228	19.8	79.5	224.0	270.7	0.2162	4.93
256	19.0	76.7	224.7	270.9	0.2380	4.98
1229	91.0	88.6	180.2	241.5	0.401	9.19
340	31.2	87.3	192.4	238.9	0.2712	5.61
580	49.2	72.6	184.0	238.7	0.3042	6.90
727	111.8	74.9	202.1	271.2	0.3560	7.74
1184	183.0	84.5	195.0	271.0	0.4075	9.88
D_p = 0.1863"	D_T = 3.79"	L = 36"			= 0.32	
G lb/ft²hr.	Re'	t_{out} °F.	t_{in} °F.	t_w °F.	$\frac{\Delta t_{in}}{\Delta t_{out}}$	Pe'
67.5	21.6	72.5	197.9	238.1	0.2430	13.60
70.0	21.0	77.0	219.4	268.6	0.2560	14.61
112.1	35.9	72.0	204.1	234.8	0.1868	9.38
176.8	55.0	79.1	216.9	268.5	0.1671	8.08
211	67.1	74.1	200.2	232.9	0.1651	7.90
168	97.1	72.7	227.3	269.0	0.2120	9.41
316	99.1	80.1	233.9	268.5	0.1735	7.98
243	171.2	70.8	229.0	269.3	0.2030	8.89
321	136.2	81.0	230.8	269.7	0.2062	9.00
709	223	77.1	226.1	268.0	0.2183	9.35
1051	334	85.0	198.7	232.6	0.2298	9.69
1947	484	90.4	222.1	267.7	0.2575	10.80

critical value of Re', the absolute values of Pe' also were experimentally less reproducible (±15%), as compared to results at higher Re' (±5%).

The comparison between the above study and the present heat-transfer analysis is striking. Figures 9 and 10 present Pe' vs. Re' from both studies in two comparable ranges of D_p/D_t. The agreement in terms of absolute value is considered excellent. In this connection it may be noted that the Pe' scale is linear which tends to exaggerate differences. This direct comparison of absolute values is possible only in the range of D_p/D_t from 0.018 to 0.16 which is the overlapping range of conditions. However, as far as curve shapes are concerned comparison between all Pe'-Re' curves of Bernard and Wilhelm and those in Figures 5, 6 and 7 for heat-transfer show a similarity in form, particularly with respect to upward trends at the extremes of Re'. It is observed, however, that below the critical Re' there is a larger degree of experimental uncertainty in the mass-diffusion experiments than in the heat-transfer experiments.

In using eddy diffusivity data for design of heat- or mass-transfer equipment it is advised that, when possible, Pe' determined in a fashion similar to the design at hand be used.

Case 2: High Conductivity Solids. The object of the preceding section was an experimental verification of the derived equations. The verification procedure was made possible by the independent availability of Pe'. The conclusion was reached that for solids of low conductivity

$$\left(k_s < 1.0 \frac{\text{B.t.u.}}{(\text{hr.})(\text{ft.})(^\circ\text{F.})}\right), K_s$$

is negligibly small. The present section is an extension of the analysis to heat-transfer experiments with solids of high conductivity (19 and 26 B.t.u./(ft.)(hr.)(° F.). These experiments have been used to determine values of K_s for this class of materials.

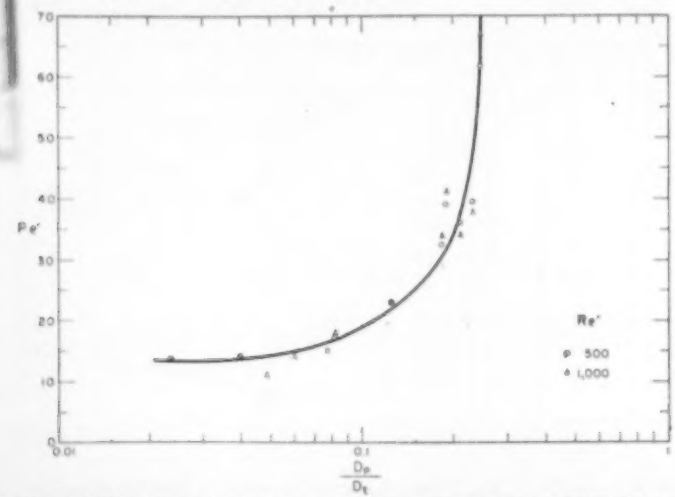

Fig. 8. Modified Peclet Numbers vs. D_p/D_t Obtained from Packed Heat Exchanger Data: Gas flowing upwards and downwards while being heated.

Experiments were performed on upflow heating of air in 3.79-in. I.D. copper tube, 36 in. in length and surrounded by a steam jacket. Packing consisted of steel ball bearings 0.188 in. and 0.344 in. in diameter and lead shot 0.178 in. and 0.332 in. in diameter. These experiments, again, were entirely comparable to those of Colburn and Leva.

From the observed values of $\Delta t_{in}/\Delta t_{out}$ values of P were determined from Figure 2. To compute K_s it was desirable to have available data regarding Pe' for particles of the same diameter as those in question. For the smaller particles Pe' was measured in the present apparatus with Socony catalyst beads, 0.184 in. in diameter (Fig. 7). For the larger particles Pe' was calculated from the data of Colburn and Leva, represented in Figure 5. With P, Pe' and $\epsilon/Re'Pr$ known and j_H obtained from Wilke and Hougen, K_s was calculated. Experimental and computed results are given in Table 6 and Figure 11. It is interesting to note that values of K_s determined in this fashion do not depend upon the sources of information for Pe'.

Some interesting observations result from Figure 11. K_s for a given material measured in this laboratory is not dependent upon D_p/D_t within the range of 0.05 to 0.09 because a single line satisfactorily represents data for the two sizes. Data of Leva* for lead shot do not correlate with the present lead-shot data. A possible explanation is offered at a later point. K_s is seen to be dependent upon Re'. At small values of Re', K_s falls rapidly to negligibly small values compared to K_e. At large values of Re', K_s flattens off and may approach values of pure metal conductivities. Surprisingly, K_s for lead shot determined in the present study is larger than that for steel balls at a given Re'. This is an apparent anomoly which needs further discussion in terms of a mechanism picture.

K_s represents a residual heat-flow path when direct fluid conductive and convective processes have been subtracted out. It is postulated that heat may flow from one particle to another in two ways: (1) through the fillet of fluid between the particles and, (2) through the metal-to-metal contact area. These two paths are in parallel. Because of the first mechanism the experimental dependence of K_s upon Re' which was obtained is a reasonable one. Furthermore, it is assumed that this path is the predominant one, an assumption which would lead to the conclusion that for the class of high conductors a single curve for K_s vs. Re' may be anticipated. Path (1) contains solid and gas conductors in series and the previous statement depends upon a low resistance in the solid compared to that in the fillet. The formation of a family of curves can result from two effects. The first is an insulating surface coating which adds to the fillet resistance in path (1) and would decrease the value of K_s at a given Re'. This is a possible explanation for the lower values found by Leva. In the present study freshly prepared and shiny lead shot was used. It is known that an oxide film forms in a relatively brief period. The second effect is that which might be brought about by solid-to-solid contact considerations of path (2). Contact conductivity depends upon the conductivity of the solids and upon contact areas between the particles. Surface coating also would contribute.

* Other metal sphere data by Colburn and by Leva and co-workers were not analyzed because large D_p/D_t ratios are involved and reliable values of Pe' are not available in this range.

Contact conductivity was studied through the analogous process of electrical conductivity of beds of steel and lead balls. A 3-in. glass cylinder resting upon a clean brass plate electrode was filled to different depth from 0 to 20 in. with spheres. An upper brass disk electrode fitting closely in the tube was brought into contact with the upper level of spheres. The electrical resistance was measured using a storage battery delivery of about 10 ma., a milliammeter and a precision potentiometer. In some experiments an electronic voltmeter was used. It was found that for both materials the resistance increased with height but leveled off toward an asymptotic value at higher bed heights. This was especially evident with lead shot. The data are presented in Table 7. The noteworthy result from Table 7 is that the electric resistance for lead shot is much smaller than for the steel ball column, presumably because of large contact area between pellets in the former case. The conclusion reached for the present is that contact point conductivity is much less important than fillet conductivity. As a result, large differences in contact conductivities (electric and hence presumably thermal) contribute but little to K_s.

The mechanism for heat flow developed here may be applied in principle to solids of low conductivity. For such a system the assumption required for the properties of path (1) and their lack of dependence on true solids conductivity, k_s is no longer tenable. Now the low conductivity of the pellets is an important factor for path (1). For cases in which k_s is small (glass, silica gel, etc.) path (1) becomes of negligible importance. Path (2) also being dependent upon k_s is now not even of secondary importance. The analysis of solids of intermediate conductivity lead to problems of the proper combinations of conductivities of fillets and spheres. Values of K_s are expected to lie between the extremes herein presented for low and high conductivity solids.

Application to Design

Resume of Theory. The preceding sections of the paper present a theoretical and mathematical background leading to design equations for packed cylindrical heat exchangers in which heat is transmitted through the containing wall to or from a stream of fluid. The effect of chemical reaction and of a flowing solid was also considered theoretically. In what follows only applications to fixed bed exchangers in the absence of chemical reaction will be discussed. The present section will serve as a design outline and at the same time as a summary of the paper.

The mechanisms proposed for heat transmission within a bed of solids are as follows:

1. Conduction in the fluid phase by molecular conductivity, k_f, and turbulent eddy conductivity, $C_p\varepsilon$. These mechanisms are in parallel.
2. Conduction in a path from particle to particle to include heat transfer through an effective fluid fillet in the zone of contact and through contact points.
3. Flow from solid particles to the fluid phase through an effective surface film resistance.
4. Transport of fluid through the bed and through the temperature gradients in the direction of flow.

These mechanisms are schematically represented in Figure 12. Differential equations based upon these ideas have been presented in Equations (10) and

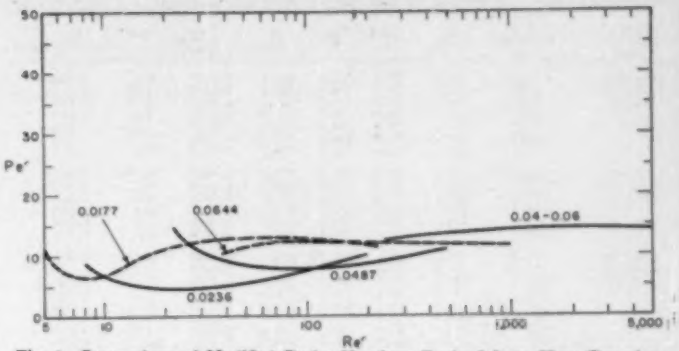

Fig. 9. Comparison of Modified Peclet Numbers Derived from Heat Transfer Data with Those Derived From Mass Diffusion Data (2).

Solid Line	Heat Transfer	Numbers are
Dashed Line	Mass Diffusion	D_p/D_T

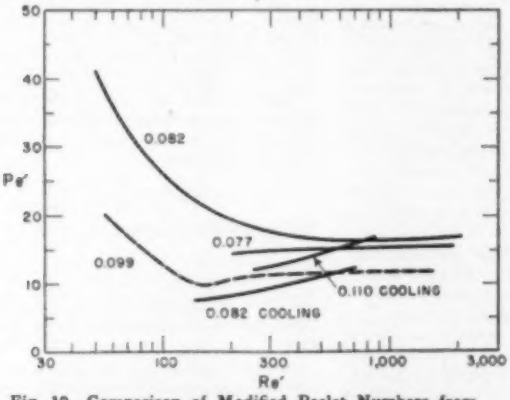

Fig. 10. Comparison of Modified Peclet Numbers from Heat Transfer Data with Those Derived from Mass-Diffusion Data (2).

Solid Line	Heat Transfer
Dashed Line	Mass Diffusion

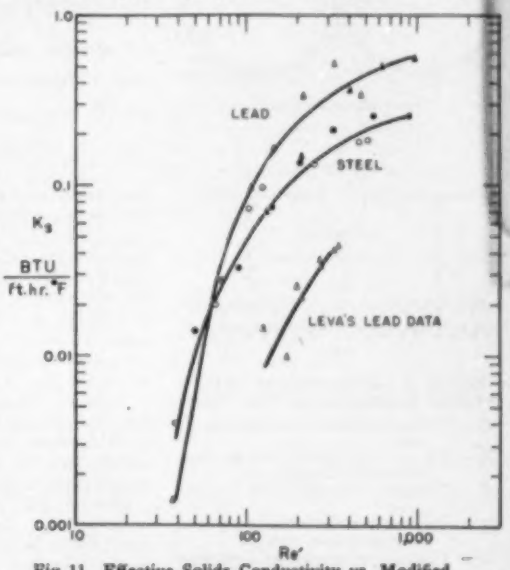

Fig 11. Effective Solids Conductivity vs. Modified Reynold's Number.

Open points	$D_p/D_T = 0.05$
Closed points	$D_p/D_T = 0.09$
Leva's points	$D_p/D_T = 0.11$

Table 6. Heat Transfer Data for Lead Shot and Steel Ball Bearings, $D_T = 3.778''$, $\xi = 36°$

	G lb/ft²hr.	Re'	t_{out} °F.	t_{ex} °F.	t_w °F.	$\frac{\Delta t_{ex}}{\Delta T_{out}}$	Pe'	K_e Btu/ft.hr.°F.
Lead Shot	121.1	37.2	72.4	211.6	244.4	0.1907	9.1	0.00140
D_p=0.1780"	219.	67.0	72.8	218.1	248.1	0.1211	7.9	0.0283
ϵ=0.365	348	104.2	70.1	253.9	270.5	0.0828	8.1	0.097
	475	141.7	72.5	256.6	270.7	0.0701	8.4	0.166
	720	214	76.6	259.1	270.2	0.0571	9.1	0.334
	1082	322	80.8	269.2	270.4	0.0961	9.7	0.521
	1535	465	90.4	218.7	236.9	0.1379	10.7	0.343
Lead Shot	130.4	71.0	76.3	234.9	270.8	0.1867	34	0.0272
D_p=0.1320"	217	128.9	74.5	245.9	270.5	0.1256	25.1	0.0695
ϵ_p= 38.1	386	208	73.6	253.2	270.4	0.0876	21.4	0.148
	729	397	74.7	256.7	244.1	0.0515	18.6	0.362
	1125	611	79.7	253.0	263.5	0.0961	18.2	0.508
	1788	990	91.8	228.1	242.5	0.0956	18.1	0.564
Steel Ball	77.5	23.4	69.4	196.8	236.8	0.2392	12.0	0.00013
Bearings	319	101.5	72.0	232.6	237.3	0.0889	8.10	0.0729
D_p=0.1861"	1584	507	96.6	213.1	237.1	0.1686	10.11	0.1841
ϵ= 0.35	118	77.9	72.4	234.1	267.3	0.1703	9.26	0.0042
	204	66.8	72.2	244.2	268.2	0.1262	8.10	0.0200
	582	190.8	71.3	251.6	268.2	0.0852	8.30	0.0975
	798	250	81.5	249.3	268.2	0.1295	9.25	0.1342
	1437	456	80.1	258.0	268.6	0.1623	10.07	0.1811
Steel Ball	84.4	49.1	79.6	228.9	271.1	0.2205	44	0.0139
Bearings	151	88	73.0	237.2	271.2	0.1736	30.3	0.0326
D_p = 0.3435"	260	139	74.7	248.0	271.0	0.1172	24.2	0.0745
ϵ = 0.40	348	204	77.1	224.1	238.2	0.0875	21.5	0.1340
	556	320	80.0	254.8	270.4	0.0820	19.6	0.213
	961	554	81.7	248.9	269.1	0.1078	18.6	0.262
	1539	901	88.1	214.9	236.0	0.1428	18.1	0.257

(31) and integrated for a point solution in Equation (26). Average mixed fluid temperatures were computed through a further integration of the point equation. The final, most generally applicable forms of this solution are repeated here as follows:

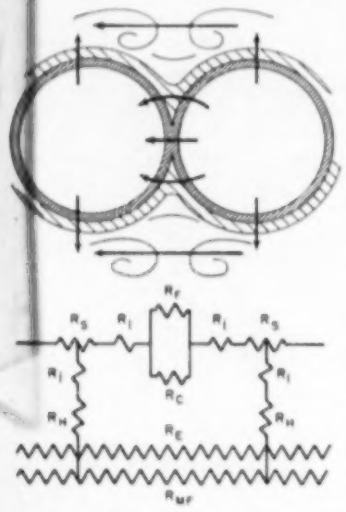

Fig. 12. Schematic Diagram of the Proposed Mechanisms for Heat Flows.

- R_s = Thermal resistance of particle itself.
- R_f = Thermal resistance of fluid fillet between particles.
- R_c = Thermal resistance of contact area.
- R_i = Thermal resistance of impurities: oxides, grease, etc.
- R_E = Thermal resistance for heat flow from particle to main body of fluid.
- R_{ur} = Thermal resistance of fluid at rest (molecular conductive effect).
- R_T = Thermal resistance of turbulent flow.

$$\frac{\Delta t_{ex}}{\Delta t_{out}} = 0.692\ exp\left[-23.14\left(\frac{1}{Re\frac{C\mu}{K_e}+\frac{3.86Pr^{\frac{1}{3}}}{j_H(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2}+\frac{\epsilon}{Re\,Pr}+\frac{1}{Pe}\right)\frac{D_p}{D_T}\frac{L}{D_T}\right] \quad (30)$$

$$\frac{h_w D_T}{k_f} = 5.79 Re\,Pr\left[\frac{1}{Re\frac{C\mu}{K_e}+\frac{3.86Pr^{\frac{1}{3}}}{j_H(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2}+\frac{\epsilon}{Re\,Pr}+\frac{1}{Pe}\right] + 0.0912\frac{G_w C D_T^2}{k_f L} \quad (31)$$

Equation (30) represents the relation between $\frac{\Delta t_{ex}}{\Delta t_{out}}$ and the mechanisms. Mechanism (1) is represented by $\frac{\epsilon}{Re\,Pr}$ for molecular conductivity and $\frac{1}{Pe}$ for eddy conductivity; mechanism (2) by $Re\frac{C\mu}{K_e}$ and mechanism (3) by $\frac{3.86Pr^{\frac{1}{3}}}{j_H(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2$. Mechanism (4) is represented within the previous expressions through Re.

Equation (31) is an alternate form of (30) which introduces h_w, an equivalent wall film transfer coefficient which has been used by previous investigators as a means of presenting experimental data. It should be noted, however, that the present analysis has shown that resistance to heat flow is a property that is distributed throughout the bed rather than concentrated at the container wall. In the present work the coefficient is utilized only for relating experimental data to the mechanisms.

Equation (30) is actually an abbreviated version of the most general Equation (28), a series solution to the differential equations. It is found that for values of $\frac{\Delta t_{ex}}{\Delta t_{out}} < 0.28$, one term of the series describes the function with a mathematical accuracy of better than 1%. Equation (30) is that one-term abbreviation. Since Equation (31) is based directly upon (30) it is subject to the same limitation. For values of $\Delta t_{ex}/\Delta t_{out} > 0.28$, one must use the complete expressions, Equations (28) and (29), with as many terms as are required for the desired accuracy.

For convenience the series Equation (28) may be represented graphically as in Figures 1 and 2 for certain cases. These cases are:

1. When $\frac{3.86Pr^{\frac{1}{3}}}{j_H(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2$ is less than 1% of $Re\frac{C\mu}{K_e}$ *or*
2. $\frac{1}{Re\frac{C\mu}{K_e}+\frac{3.86Pr^{\frac{1}{3}}}{j_H(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2}$ is negligible (less than 1-5%) compared to $\left[\frac{\epsilon}{Re\,Pr}+\frac{1}{Pe}\right]$

For these cases, Figures 1 and 2, represent the series with sufficient terms to accomplish a mathematical accuracy of better than 1%. The variables plotted are $\Delta t_{ex}/\Delta t_{out}$ and P where

$$P = \left[\frac{1}{Re\frac{C\mu}{K_e}+\frac{\epsilon}{Re\,Pr}+\frac{1}{Pe}}\right]\frac{D_p}{D_T}\frac{L}{D_T}$$

Case 1

$$= \left[\frac{\epsilon}{Re\,Pr}+\frac{1}{Pe}\right]\frac{D_p}{D_T}\frac{L}{D_T}$$

Case 2

Sources of Data. For solution of packed heat-exchanger problems four thermal rate constants must be at hand. The constants are

$$Pe\left(=\frac{D_p V}{E}\right)$$

for turbulent conduction,

$$Pr\left(=\frac{C\mu}{k_f}\right)$$

for molecular conduction, K_s for conduction in the solid path and h_c for particle-to-fluid film transfer.

Pe: This constant may be obtained from two analogous types of measurements, heat transfer and mass transfer. *Pe* from heat-transfer sources is obtained through the applications of the equations presented in this paper to packed exchanger data. Results for spherical packing from the data of Colburn, Leva and the authors are given

in Figures 5-7. Heat-exchanger data by Leva (*15*) for cylindrical particles and for mixed sizes of spheres are available but values of $P\acute{e}$ have not been computed. $P\acute{e}$ from mass-transfer measurements have been reported by Bernard and Wilhelm (*2*). As shown in this paper, $P\acute{e}$ from heat and mass transfer are consistent with each other. However, for greatest design precision it is advised that, when possible, $P\acute{e}$ determined in a manner similar to the process under consideration be employed.

Pr: Values of molecular thermal conductivity, represented through Pr, may be obtained from standard reference sources.

K_s: Analysis of heat-exchanger data available has shown that the solid-to-solid conduction may be characterized by the conductivity of the substance of the solid particles. The following observations have been made:

a. Materials of low conductivity such as glass, ceramics, sand, and catalyst supports form a class having low true conductivities, k_s, in the range from 0.1 to 1.0 B.t.u./(ft.)(hr.)(° F.). Within this class the value of K_s is negligibly small compared to the other modes of conduction.

b. Materials of high conductivity such as lead and steel with conductivities of 19 and 26 B.t.u./(ft.)(hr.)(° F.) respectively, form a class for which K_s is significant. For this class of materials K_s is dependent upon $R\acute{e}$, upon surface impurities, such as corrosion products, and, to a less extent, upon the area of the contact points. The variation of K_s with $R\acute{e}$ is shown in Figure 11.

It will be noted that only gas-solid systems are represented in the present study; the effect of higher conductivity fluids remains to be investigated. Also solid materials with conductivities between the two extremes represented above have not been treated.

h_w: By direct measurement the solid-to-fluid coefficient is available for gases through the studies of Hougen and coworkers (*7, 24*) and Hurt (*12*). A liquid-solid system was investigated by McCune and Wilhelm (*19*). The h_w here used differs from that presented by the above-named authors by a term representing area/volume.

Illustrative Examples:

Problem (1): It is desired to heat air in a packed bed heater from an initial temperature of 70° F. to a final temperature of 200° F. using 10 lb./sq.in. saturated steam in the jacket. The total air flow is 30 std. cu.ft./min. (70° F., 14.7 lb./sq.in.). Packing material is ½-in. gravel. The heater is to be made of 4-in. standard steel pipe. What length is required? Also estimate the length required for ½-in. steel balls as packing.

Solution:

$$\frac{\Delta t_{ss}}{\Delta t_{sa}} = \frac{240.1 - 200}{240.1 - 70} = 0.236$$

There is a choice of equivalent procedures:

a. Because K_s for gravel is small, Figures 1 or 2 may be employed.

b. Because $\Delta t_{ss}/\Delta t_{sa}$ is less than 0.28, Equation (30) may be used.

Selecting the first of these procedures, from Figure 1

$$P = 0.0473$$

$$\frac{D_p}{D_t} = \frac{0.200}{4.03} = 0.0496$$

$$G_a = \frac{(30)(60)(0.0808)(144)(492)}{(.786)(4.03)^2(530)} = 1524 \frac{\text{lb.}}{\text{sq.ft.hr.}}$$

Average air temperature = 135° F.

$$\mu_{135°F} = 0.0191 \text{ cp.}$$

$$R\acute{e} = \frac{(0.200)(1524)}{(12)(0.0191)(2.42)} = 550$$

from Figure 5, $P\acute{e} = 10.91$; $\frac{1}{P\acute{e}} = 0.0916$

Estimate $\epsilon = 0.40$ $\quad Pr = 0.74$

$$\frac{\epsilon}{R\acute{e}Pr} = 0.0010$$

$$P = \left[\frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right]\frac{D_p}{D_T}\frac{L}{D_t} = 0.0473$$

$$= [0.0010 + 0.0916](0.0496)\left(\frac{L}{4.03}\right)$$

$L = 41.5$ in.

To demonstrate the effect of an error in the determination of $P\acute{e}$ assume $P\acute{e} = 11.9$ representing a variation of one unit from the above example. With a tube 41.5 in. in length an exit temperature of 195° F. would be secured instead of 200° F.

Assuming steel balls instead of gravel in the above problem, the procedure is as follows:

$\Delta t_{ss}/\Delta t_{sa} = 0.236$, is less than 0.28 permitting use of Equation (30) or Figures 1 and 2. From Figure 1, $P = 0.0473$.

From Figure 11, $K_s = 0.225$ B.t.u./(ft.)(hr.)(° F.).

$$R\acute{e}\frac{C_p}{K_s} = 550\frac{0.237 \times 0.0191 \times 2.42}{0.225} = 26.8$$

From Reference (*24*) at

$$R\acute{e} = 550, \quad j_H = 0.0745.$$

$$S_s = \frac{3.85(Pr)^{⅔}}{(1-\epsilon)j_H}\left(\frac{D_p}{D_t}\right)^2 = 0.174 = 0.2$$

$$\frac{1}{R\acute{e}\frac{C_p}{K_s} + S_s} = \frac{1}{26.8 + 0.2} = 0.0370$$

$$P = \left[\frac{1}{R\acute{e}\frac{C_p}{K_s} + \frac{3.85(Pr)^{⅔}}{(1-\epsilon)j_H}\left(\frac{D_p}{D_t}\right)^2} + \frac{\epsilon}{R\acute{e}Pr} + \frac{1}{P\acute{e}}\right]\frac{D_p}{D_t}\frac{L}{D_t}$$

$$0.0473 = [0.0370 + 0.0010 + 0.0916](0.0496)\left(\frac{L}{4.03}\right)$$

$$L = 29.7 \text{ in.}$$

Problem 2. When $\Delta t_{ss}/\Delta t_{sa}$ is larger than 0.28 and K_s is significant, the calculations become more extensive than for Problem 1. The following solution is outlined to demonstrate the mode of procedure.

Design a heat exchanger to heat air from 70° F. to 155° F. using 10 lb./sq.in. saturated steam in the jacket. The total air flow is 30 std.cu.ft./min.(70° F., 14.7 lb./sq.in.). Packing material is ½-in. steel balls. Tube walls are made of 4-in. standard steel pipe. What is the length required?

Solution:

$$\frac{\Delta t_{ss}}{\Delta t_{sa}} = \frac{240.1 - 155}{240.1 - 70} = 0.50$$

Because $\Delta t_{ss}/\Delta t_{sa} > 0.28$ and K_s is significant, it is necessary to use the complete Equation (28).

$R\acute{e} = 550\frac{D_p}{D_T} = 0.0496$ $\quad D_T = 4.03$ in.

From Figure 5,

$P\acute{e} = 10.9$ $\quad 1/P\acute{e} = 0.0916$

Estimate $\epsilon = 0.40$

$$\frac{\epsilon}{R\acute{e}Pr} = 0.0010$$

From Figure 11, $K_s = 0.225$ B.t.u./(ft.)(hr.)(° F.)

TABLE 7.—ELECTRICAL RESISTANCE OF COLUMNS OF STEEL AND LEAD BALLS

	Height, in.	Total Resistance, ohms
Lead Balls		
$D_p/D_t = 0.059$	1	0.31
	2.6	0.42
	3.7	0.48
	6.9	0.52
	15.8	0.61
$D_p/D_t = 0.11$	1.5	0.3
	5.6	0.4
	9.5	0.5
	19.3	0.6
Steel Balls		
$D_p/D_t = 0.060$	0.9	4,200
	2.0	28,000
	4.0	38,000
	9.2	27,000
	9.8	19,000
	19.4	20,500

$$R\acute{e}\frac{C_p}{K_s} = 26.8$$

From Reference 24 at $R\acute{e} = 550$,

$$j_H = 0.0745$$

$$\frac{(Pr)^{⅔}}{(1-\epsilon)j_H}\left(\frac{D_p}{D_T}\right)^2 = 0.0451$$

$$S_s = ⅔\frac{\mu_s^2(Pr)^{⅔}}{(1-\epsilon)j_H}\left(\frac{D_p}{D_T}\right)^2$$

Values of $⅔\mu_s^2$ are listed in Table 2.

It will be recognized that the solution will be a trial-and-error type. The calculations are summarized in Table A.

Acknowledgments

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Notation

Dimensional Units

- L = length
- M = mass
- H = quantity of heat
- θ = time
- d = temperature
- A_r = constants in Eq. (16)(d)
- A_T = area of wall of tube (L^2)
- A = frequency factor in kinetic expression (same dimensions as reaction rate constant)
- C = heat capacity of fluid $\left(\frac{H}{Md}\right)$
- C_s = heat capacity of solid $\left(\frac{H}{Md}\right)$
- C_A, C_B = concentration of reactants $\left(\frac{M}{L^3}\right)$

TABLE A

No. of Term	$\frac{2}{0}\rho^2$	B_n	$\frac{1}{\frac{RéC_p}{K_e}+B_n}$	$\left[\frac{1}{\frac{RéC_p}{K_e}+B_n}+\frac{8}{RéPr}+\frac{1}{Pé}\right]\frac{DpL}{DrDT}$	Value of n'^{th} Term: General	Assumed L (in.)	Assumed Value of Term
1	2.86	0.2	0.0370	0.001592L	$0.692e^{-0.0001L}$	20	0.331
						15	0.398
						10	0.479
						8	0.515
2	30.51	0.9	0.0361	0.001583L	$0.131e^{-0.0006L}$	20	0.003
						15	0.007
						10	0.019
						8	0.027
3	49.9	2.2	0.0344	0.001562L	$0.053e^{-0.0011L}$	20	5×10^{-6}
						15	5×10^{-6}
						10	0.0005
						8	0.001
Sum of Terms 1, 2, 3	.....	...	.....	.....	.....	20	0.334
						15	0.405
						10	0.498
						8	0.543

Sums of the last column for any assumed value of L give the predicted value of $\Delta t_{ex}/\Delta t_{int}$. A plot of $\Delta t_{ex}/\Delta t_{int}$ vs. L gives a value of $\Delta t_{ex}/\Delta t_{int} = 0.500$ at $L = 9.9$ in.

C_{A1} = initial concentration of key reactant $\left(\frac{M}{L^3}\right)$

D_p = particle diameter (L)

D_T = tube diameter (L)

E = eddy diffusivity $\left(\frac{L^2}{\theta}\right)$

E_a = energy of activation $\left(\frac{H}{M}\right)$

f = fraction conversion of key reactant (dimensionless)

G' = mass velocity of fluid $\left(\frac{M}{L^2\theta}\right)$

G_r = mass velocity of fluid in radial direction $\left(\frac{M}{L^2\theta}\right)$

$G_z = G_o$ = superficial mass velocity in axial direction $\left(\frac{M}{L^2\theta}\right)$

G_ϕ = mass velocity in circular direction in plane perpendicular to the axis $\left(\frac{M}{L^2\theta}\right)$

h_H = area heat-transfer coefficient from particle to fluid $\left(\frac{H}{L^2\theta d}\right)$

h_v = volumetric heat-transfer coefficient from particle to fluid $\left(\frac{H}{L^3\theta d}\right)$

h_w = heat-transfer coefficient from wall to fluid based on tube wall area $\left(\frac{H}{L^2\theta d}\right)$

ΔH = heat of reaction per mole of key reactant — negative value indicates exothermic reaction $\left(\frac{H}{M}\right)$

J_o = zero th order Bessel function, first kind

J_1 = first-order Bessel function, first kind

$j_H = \left(\frac{h_H}{G_o C}\right)\left(\frac{C_\mu}{k_f}\right)^{2/3}$ = j factor for heat transfer (dimensionless)

k_f = molecular fluid conductivity $\left(\frac{H}{L\theta d}\right)$

K_f = effective fluid conductivity $\left(\frac{H}{L\theta d}\right)$

k_s = molecular solid conductivity $\left(\frac{H}{L\theta d}\right)$

K_s = effective solid conductivity $\left(\frac{H}{L\theta d}\right)$

k_r = roots of $J_o(k) = 0$ (dimensionless)

k = Boltzmann constant $\left(\frac{H}{d}\right)$

k_L = mass-transfer coefficient between particles and flowing liquid $\left(\frac{M}{L^2\theta M/L^3}\right)$

L = total height of reactor or heat exchanger (L)

M_A = molecular weight of key reactant (M)

$Pr = \frac{C_\mu}{k_f}$ = Prandtl group (dimensionless)

$Pé = \frac{D_p V}{E}$ = modified Peclet group (dimensionless)

P = rate group for static bed exchanger (dimensionless)

q = heat flow from wall of tube to fluid $\left(\frac{H}{\theta}\right)$

Q_n = rate group for moving bed exchanger (dimensionless)

R^* = rate of reaction $\left(\frac{M}{L^3\theta}\right)$

$R^*\Delta H = C_o + C_1 t_s \left(\frac{H}{L^3\theta}\right)$

r = radial position (L)

R_T = radius of tube (L)

$Ré$ = modified Reynolds Number $\frac{D_p G_o}{\mu}$ (dimensionless)

R_w = rate of reaction at wall temperature $\left(\frac{H}{L^3\theta}\right)$

$S_n = \frac{2}{3}\rho_n^2 \frac{P_T{}^2}{j_H(1-\epsilon)}\left(\frac{D_p}{D_T}\right)^2$ (dimensionless)

S_o = superficial mass velocity of solid $\left(\frac{M}{L^2\theta}\right)$ in axial direction

t_f = fluid temperature (d)

t_s = solid temperature (d)

t_{ent} = mean entrance temperature of fluid (d)

t_{ex} = mean exit temperature of fluid (d)

t_w = wall temperature (d)

t_v = steam temperature (d)

$\Delta t_{ent} = t_w - t_{ent}(d)$

$\Delta t_{ex} = t_w - t_{ex}(d)$

Δt_{lm} = log mean-temperature difference between wall and fluid (d)

T_n = rate group for moving bed exchanger (dimensionless)

$u_{o,1,2,\ldots,n}$ = functions of x used in evaluating $t_s(d)$

$v_{o,1,2,\ldots,n}$ = functions of x used in evaluating $t_f(d)$

V = superficial linear velocity of fluid $\left(\frac{L}{\theta}\right)$

W_n = rate group for static bed reactor (dimensionless)

x = axial position (L)

$y = \frac{r}{R_T}$ (dimensionless)

C_o = constant in expression $R^*\Delta H = C_o + C_1 t_s \left(\frac{H}{L^3\theta}\right)$

C_1 = constant in above expression $\left(\frac{H}{L^3\theta d}\right)$

α_n = constants used in evaluating $t_s, t_f = \left(\frac{\rho_n}{R_T}\right)(L^{-1})$

ϕ = angular position (dimensionless)

ρ = fluid density $\left(\frac{M}{L^3}\right)$

ρ_n = n'th root of $J_o(\rho) = 0$ (dimensionless)

ϵ = fraction void space (dimensionless)

μ = fluid viscosity $\left(\frac{M}{L\theta}\right)$

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Discussion

J. M. Smith (Purdue University, Lafayette, Ind.): In the integration of the differential equations were constant values assumed for the physical properties and various conductivities?

E. Singer: Yes, that is true.

J. M. Smith: In view of that, is it possible that variations in mass flow rate across the diameter of the tube and possible variations in temperature radially might have an effect upon the results?

E. Singer: The question involved is the validity of the assumption that the physical parameters are constant throughout the confines of the bed. We have tested this assumption by referring to the heat-transfer data for exchangers of varying dimensions packed with materials of varying particle diameters. The logical parameter for the modified Peclet group is the particle-to-tube diameter ratio. If the variation in physical parameters at different points in the bed is significant, the modified Peclet groups calculated on the assumption of the constancy of these parameters would depend upon the length of the bed, the diameter of the bed, the particle size and the absolute value of the wall-fluid temperature difference. However, in the plots shown, each one of the curves represents data for quite different lengths of bed, different tube diameters, and different particle diameters. The only parameter which affects the value of $Pé$ for a given $Ré$ is the value of D_p/D_T. Figures 3 and 4 were drawn specifically to illustrate this point. We feel, therefore, that any variation in the physical parameters produces a negligible effect for the systems studied.

Ovid Baker (Magnolia Petroleum Co., Dallas, Tex.): I received the impression that the authors expect some additional heat to be transferred due to radiation at high temperature levels, although they present no term for this mechanism. Heat probably is radiated from particle to particle across the void spaces in the bed. Apparently the amount of heat transferred by radiation is small compared to the other mechanisms. Several years ago we made several experiments to check the effect of temperature level on heat transfer in externally heated packed tubes. Our results were very similar to those of Colburn (*3*) (Lit. Ref. in paper) as shown in Table B for a 0.742-in. I.D. tube. Apparently radiation made little difference at these conditions.

At these high temperatures the heat-transfer coefficient is still proportional to the mass velocity to the 0.8 power. These data are given below. The ratio of particle diameter to tube diameter should allow radiation to pass very readily. The experiments with air were conducted with porcelain cylinders as packing. The packing in the natural gas experiments was high emissivity carbon impregnated line particles. See Table C.

Thomas Baron (University of Illinois, Urbana, Ill.): We have done some work at the University of Illinois and we can show that provided the most important mechanism in the transfer proper is the mechanism of carrying around of heat by the winding motion of the fluid around the particles. Provided that this is the most important mechanism, the Peclet number should be a constant and should be independent of the velocity, particle diameter and in fact, any of the properties of the beds and the fluid. We can also show that in this case the value of the Peclet number should be 10, irrespective of what kind of a packing you have, possibly slightly affected by shape factors and quite independent of the type of fluid and temperature, etc. Would you agree that in the cases of Peclet number of 10 and reasonably constant with Reynolds number, that that indicated that the diffusivity was due to this "random walk" motion in the bed.

E. Singer: I think that is probably true. We have made studies also in this direction and have arrived at similar conclusions. The deviation of $Pé$ for the large particles from the theoretical value of about 10 is thought to result from two causes. The first is the onset of a much looser packing with large values of D_p/D_t. The second is the lack of concordance with the basic assumption in the "random walk" treatment. This assumption is that many steps are involved in progressing from the source to a given point. The line at the top of Figure 5 is for $D_p/D_t = 0.25$. It takes only four particles to equal one diameter. Consequently, we believe that the random walk considerations would no longer be valid. On the other hand, for $D_p/D_t = 0.04$ the random walk considerations are appropriate.

(*Presented at Eleventh Regional Meeting, Tulsa, Okla.*)

TABLE B

Gas	Mass Velocity lb./(hr.)(sq.ft.)	Temperature Level, °F.	$\left(\frac{h(\text{packed tube})}{h(\text{empty tube})}\right)$	D_p/D_t	Source
Air	3600	266	4.1	0.29	Colburn (3)
Air	3600	386	4.9	0.34	Colburn (3)
Air	3600	1450	4.2	0.39	Magnolia
Natural gas	3600	1300	3.5	0.34	Magnolia

TABLE C

Mass Velocity lb./(hr.)(sq.ft.)	h B.t.u./(hr.)(sq.ft.)(° F.)	D_p/D_t	Gas Temperatures ° F. Entering	Leaving	Gas
1500	11.3	0.25	760	1925	Air
2375	19.2	0.35	600	1945	Air
3305	23.5	0.35	800	1900	Air
3305	26.0	0.25	560	1945	Air
5550	31.3	0.35	560	1920	Air
6950	44.7	0.25	400	1820	Air
540	12.0	0.34	650	1820	Natural Gas
2740	52.9	0.34	500	1800	Natural Gas (24.8% H_2 in effluent gas)
3617	60.8	0.34	450	1885	Natural Gas (19.2% H_2 in effluent gas)
4950	85.2	0.34	400	1580	Natural Gas (12.9% H_2 in effluent gas)

SIMPLE TURBINES IN FULLY BAFFLED TANKS

Power Characteristics

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Turbines, having two, four and six flat rectangular blades of various dimensions were tested for power consumption at various speeds in the turbulent region (baffled), and also in the viscous flow region. It was found that the turbines could be correlated by the general form:

$$Pg_c = KN^3L^{5-b}W^b\rho$$

for the turbulent region and by the form:

$$Pg_c = K'N^2L^{3-b'}W^{b'}\mu$$

for the viscous region.

Constants, K, K', b, and b', were found to be functions of the number of blades.

RELATIONS between the power, speed, and diameter for geometrically similar turbines rotating in Newtonian liquids have been well investigated (*1-9*). The mathematical relations which govern the general cases are:

For viscous flow:

$$Pg_c = \text{const } N^2L^3\mu$$

(for similar impellers) (1)

For turbulent flow in unbaffled vessels:

$$Pg_c = \text{const } N^{2.83}L^{4.70}\rho^{.83}\mu^{.15}$$

(for similar impellers and tanks) (2)

For fully baffled turbulent flow:

$$Pg_c = \text{const}N^3L^5\rho$$

(for similar impellers) (3)

It is the purpose of this work to show the relation between the power and the dimensions (length, width, and number of blades), for simple turbines. Turbines chosen for study were of the hubless rectangular-blade type with the blades at a 90° angle to the plane of rotation. The simple paddle is an example of a two-blade type of turbine.

The turbines were run in water and in kerosene for the determinations in the turbulent region, and in a heavy glucose solution (Karo) for the determinations in the viscous region. No tests were made in the transition region between the viscous and turbulent regions.

Several sets of similar two-, four-, and six-blade turbines with various length-width ratios were used. At all times sufficient baffling was used to produce fully baffled conditions (*2*).

Table 1 shows the range of the variables studied.

Test apparatus: (*See* Fig. 1). A variable speed, ⅓-hp. motor was used as the power source. This motor was connected directly to the turbine shaft and was mounted on a ball-bearing turntable. This turntable was simply a pure thrust-bearing containing a few ½-in. steel balls separated by 7/16-in. balls and lubricated with a small quantity of clock oil. The motor leads were suspended from a point about 3 ft. directly above the motor so that they had a negligible effect on torque readings. The friction in the pulley was also found to be negligible. The tendency of the motor to turn was transmitted to a balance through a pulley and the torque obtained thereby. A triple-beam laboratory balance sensitive to about 0.1 g. and which could weigh up to 610 g. was used for this measurement. Higher readings were made by placing special weights on the beam of the balance.

The controlling source of error was in the static friction of the bearing. On the average this amounted to about 30 g. in the balance reading. To correct for this, weights were added to the balance until the pointer dropped, and then weights were removed from the balance until the pointer rose. The average of these two readings was then taken as the true torque reading corrected for static friction in the bearing. The motor was placed in such

NOTE: Supplemental and experimental data comprising Tables 2, 3 and 4 are on file (Document 2751) with the American Documentation Institute, 1719 N Street, N.W., Washington 6, D. C. Data can be obtained by remitting 50 cents for microfilm or $2.70 for photocopies.

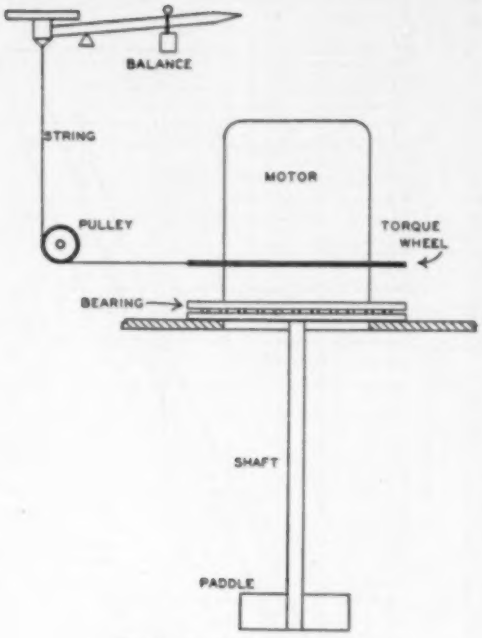

Fig. 1. Dynamometer System.

a position on the bearing that the static friction was the same in either direction, and readings were taken with the motor running both clockwise and counterclockwise. Thus consistent errors were cancelled, leaving only random error. No-load torque (shaft turning in fluid without turbine) was in each case subtracted from the observed torque to obtain the true value.

The viscosity of the glucose solutions was obtained by means of a Stormer viscosimeter, which had been calibrated with standard castor oil. The temperature of the liquid during the tests rose to no more than 0.8° C. due to the energy liberated during the agitation. The viscosity used in the correlation was that of the mean temperature. The viscosity of this material changed about 3% for each 0.5° C. temperature change.

The viscosities of water and kerosene were obtained from the "Chemical Engineers' Handbook." Densities were determined by means of a Westphal balance.

Only one tank and one set of baffles were used as it has been shown previously that the power consumed in the fully baffled turbulent range and in the viscous range is independent of the size of the tank and number and type of baffles. Therefore, the data obtained in this work may be applied to all sizes of fully baffled tanks, and thus the correlations obtained herefrom are generally applicable for these types of fluid flow.

TABLE 1.—RANGE OF VARIABLES TESTED AND EQUIPMENT DIMENSIONS

Variable	Symbol	Range
Shaft speed	N	7-2000 rev./min.
Density	ρ	0.8–1.36 g./cc.
Viscosity	μ	1-500 cp.
Paddle length	L	3.47–6.00 in.
Paddle width	W	0.25–3.47 in.
No. of blades	S	2, 4, and 6
Power	P	0.0000276–0.1836 hp.
Tank diameter		9–9/16 in.
Liquid depth		23 in.
Mode of baffling		3 baffles, 90° with tank wall, 4 in. wide
Distance of impeller from tank bottom		3 in.
Shaft diameter		¾ in.
Blade thickness		⅛ in.

Results of Tests

Turbulent Region. Plots of power versus speed gave slopes of three on logarithmic coordinates, showing that fully turbulent conditions were obtained. Examples of such plots are shown in Figure 2. Data obtained in the turbulent region appear in Tables 2 and 3. Any geometrically similar series of impellers gave the usual correlation of

$$Pg_c = \text{const}\ N^3L^5\rho \qquad (4)$$

For a particular number of blades, it was found that the various width-length ratios could be correlated with $Pg_c/N^3L^5\rho$ by using the term $(W/L)^b$, where b is a function of the number of blades, giving the equation,

$$\frac{Pg_c}{N^3L^5\rho} = \text{const}\left(\frac{W}{L}\right)^b$$

This relation is shown in the plot of experimental data in Figure 4. Accordingly:

For 2 blades:

$$Pg_c = 13.8N^3L^{3.77}W^{1.23}\rho \qquad (5)$$

For 4 blades:

$$Pg_c = 19.4N^3L^{3.85}W^{1.15}\rho \qquad (6)$$

For 6 blades:

$$Pg_c = 23.7N^3L^{3.91}W^{1.09}\rho \qquad (7)$$

For S blades:

$$\frac{Pg_c}{N^3L^5\rho} = (9.74S^{-0.695})\left(\frac{W}{L}\right)^{1.328S^{-0.305}} \qquad (8)$$

It must be emphasized that these equation constants hold only for the fully baffled turbulent state.

Viscous Region. Plots of power versus speed gave slopes of two on logarithmic coordinates at the lower speeds, showing that the power was varying as the square of the speed, as should be the case for viscous flow. Data at the higher speeds which gave a slope of greater than two, showing that the flow was changing from viscous to turbulent, were not used in the correlation. (*See* Fig. 3.) Data obtained for this region appear in Table 4. Any geometrically similar series of impellers gave the expected correlation of

$$Pg_c = \text{const}\ N^2L^3\mu \qquad (9)$$

In a manner similar to that previously mentioned, the equation correlating the width-length ratios was found to be

$$\frac{Pg_c}{N^2L^5\rho} = \text{const}\left(\frac{\mu}{NL^2\rho}\right)\left(\frac{W}{L}\right)^{b'}$$

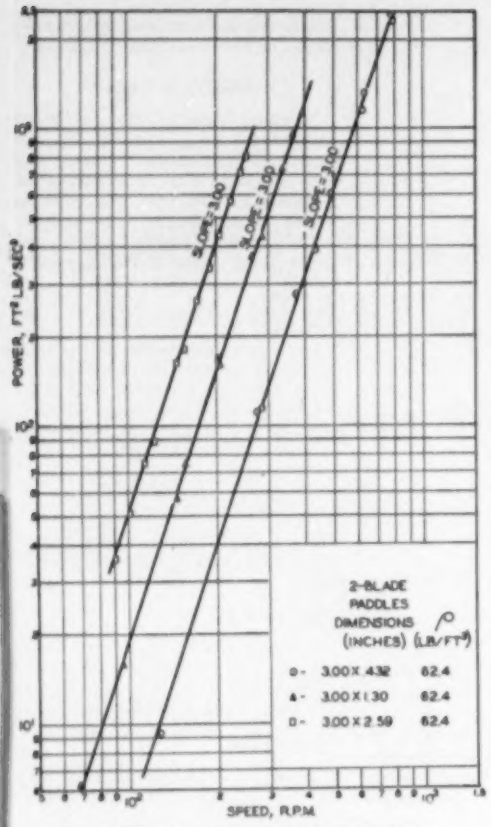

Fig. 2. Power vs. Speed, Turbulent Conditions.

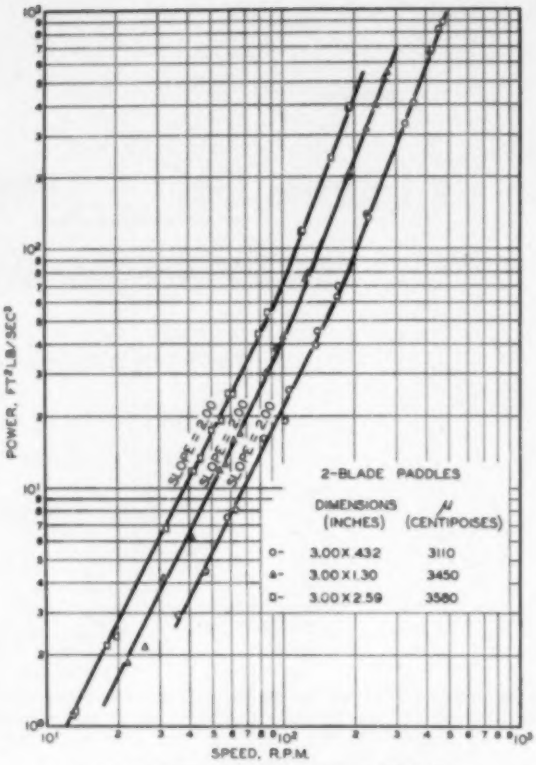

Fig. 3. Power vs. Speed, Viscous Conditions.

where b' is a function of the number of blades. This relation is shown in the plot of experimental data in Figure 5. Accordingly:

For 2 blades:

$$Pg_c = 113N^3L^{2.48}W^{.52}\mu \qquad (10)$$

For 4 blades:

$$Pg_c = 141N^3L^{2.55}W^{.45}\mu \qquad (11)$$

For 6 blades:

$$Pg_c = 161N^3L^{2.62}W^{.38}\mu \qquad (12)$$

For S blades:

$$\frac{Pg_c}{N^3L^5\rho} = (90.0S^{.327})\left(\frac{\mu}{NL^2\rho}\right)\left(\frac{W}{L}\right)^{.635S^{-.200}} \qquad (13)$$

Comment

Equations shown for S blades are of doubtful practical value, but they do allow all data to be plotted together to show the consistency of the experimental data as shown in Figure 6. For viscous flow 338 points were plotted of which 90% were within a deviation of ±15%. For the fully baffled turbulent flow 381 points were plotted of which 94% were with a deviation of ±15% from the mean.

It is felt that the deviations are purely random and that the best lines (least squares method) through the many experimental points is a proper representation of the true values. The deviations are attributed to the insensitivity of the power-measuring device and were not due to erratic behavior of the impellers.

To anticipate where the transition from viscous to turbulent flow *starts* only equate pairs of equations are needed of the form,

$$\frac{Pg_c}{N^3L^5\rho} = \text{const}\left(\frac{\mu}{NL^2\rho}\right)\left(\frac{W}{L}\right)^{b'}$$

for viscous flow and

$$\frac{Pg_c}{N^3L^5\rho} = \text{const}\left(\frac{W}{L}\right)^{b}$$

for turbulent flow. Therefore for S-blade turbines:

$$\frac{Pg_c}{N^3L^5\rho} = 90.0S^{.327}\left(\frac{\mu}{NL^2\rho}\right)\left(\frac{W}{L}\right)^{.634S^{-.200}} = 9.74S^{.495}\left(\frac{W}{L}\right)^{1.33S^{-.100}}$$

and

$$\left(\frac{NL^2\rho}{\mu}\right)_{\text{transition}} = 9.25S^{-.168}\left(\frac{W}{L}\right)^{(.635S^{-.200}-.133S^{-.100})} \qquad (14)$$

Equation (14) is not to be taken as a prediction of a definite transition point from viscous to turbulent flow but merely an indication of where it may start. Moreover the critical region is

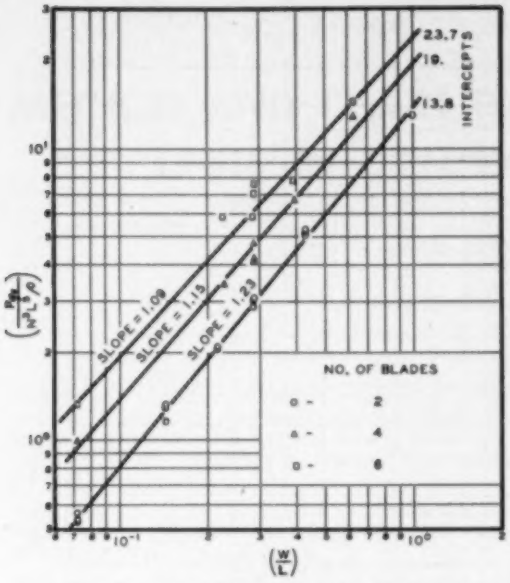

Fig. 4. Power Function vs. Shape Ratio, Turbulent Conditions.

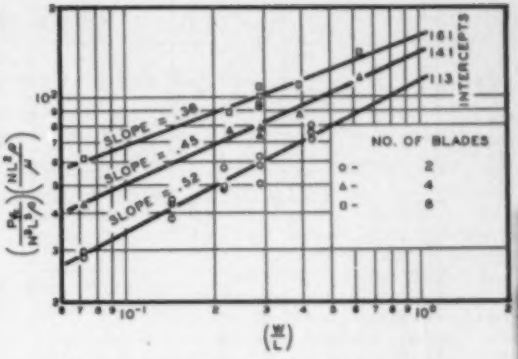

Fig. 5. Power vs. Shape Ratio, Viscous Conditions.

seldom a sharp point but a long, smooth curve which is roughly tangent to the viscous and turbulent lines and may begin before such an anticipation point. The transition from viscous to turbulent is usually completed at a Reynolds number of about 10,000 (*1, 5*), but it is indefinite and depends somewhat on the mode of baffling. Data used for the analysis of the turbulent flow region were all chosen to give Reynolds numbers of greater than 10,000.

The following examples illustrate how the results may be used.

1. In a tank 6 ft. in diameter with a liquid depth of 6 ft. a liquid slurry (sp.gr. 1.07, viscosity 1 cp.) is to be agitated. A 3-hp. motor with a 20:1 speed reducer is available for the job. The full load speed of the motor is 1000 rev./min. and the transmission efficiency of the speed reducer is 90%. The tank is to be fully baffled.

Problem: Arrive at suitable dimensions for a 4-blade paddle which will draw a full load from the motor.

Solution: The length of the paddle will be made as great as possible to give a maximum peripheral velocity. Allowing 1/10 of the tank diameter for the protrusion of the baffles will permit a paddle diameter, L, of 4 ft.

Agitation power,

$$P = (3)(.9)(33{,}000)$$

$$= 89{,}200\ \frac{\text{(ft. lb.)(force)}}{\text{min.}}$$

Impeller speed,

$$N = (1000)(1/20) = 50\ \text{rev./min.}$$

Fluid density,

$$\rho = (1.07)(62.5) = 66.9\ \text{lb. (mass)/cu.ft.}$$

Gravitational conversion factor,

$$g_c = (32.2)(3600)\ \frac{\text{ft.}}{\text{(min.)(min.)}}\ \frac{\text{lb.(mass)}}{\text{lb.(force)}}$$

According to Equation (6)

$$Pg_c = 19.4N^3L^{4.60}W^{1.15}\rho$$

or

$$W = \left(\frac{Pg_c}{19.4N^3L^{4.60}\rho}\right)\frac{1}{1.15}$$

$$W = \left(\frac{(89{,}200)(32.2)(3600)}{(19.4)(50)^3(4)^{4.60}(66.9)}\right)^{.87}$$

$$= .300\ \text{ft. } 3.6\ \text{in.}$$

Thus the dimensions of the 4-blade paddle will be

$$W = 3.6\ \text{in.}$$

$$L = 4\ \text{ft.}$$

It should be noted that under fully baffled conditions, as above, the viscosity of the liquid does not enter into the calculation.

2. A 2-blade flat paddle has been used in a solution of specific gravity 1.0. This agitator is to be used with a liquid of specific gravity 1.86. Fully baffled turbulence prevails under the conditions of operation.

Problem: How much should the blades be cut off to prevent overloading of the agitator motor, assuming that it was operating at full capacity with the first liquid.

Solution: According to Equation (5)

$$Pg_c = 13.8\ N^3L^{4.77}W^{1.00}\rho$$

or under the conditions of the problem,

$$L^{4.77} \propto \frac{1}{\rho}$$

and

$$\left(\frac{L_{1.86}}{L_{1.0}}\right)^{4.77} = \frac{1.0}{1.86} = .537$$

$$\left(\frac{L_{1.86}}{L_{1.0}}\right) = .85;\ 85\%$$

or the blades should be cut off 15%.

It should be noted that no power measurements were necessary for this calculation.

3. A heavy syrup of specific gravity .98, viscosity 30,000 cp. is to be agitated by a 4-blade impeller of 2 ft. diameter and 3-in. width at 60 rev./min.

Problem: (a) Is this viscous or turbulent operation?

(b) What is the power requirement for this operation?

Solution: (a) According to Equation (14)

$$\left(\frac{NL^2\rho}{\mu}\right)_{\text{transition}} = 9.25S^{-.500}\left(\frac{W}{L}\right)^{(.600\ -\ .500\ -\ .500\ -\ .500)}$$

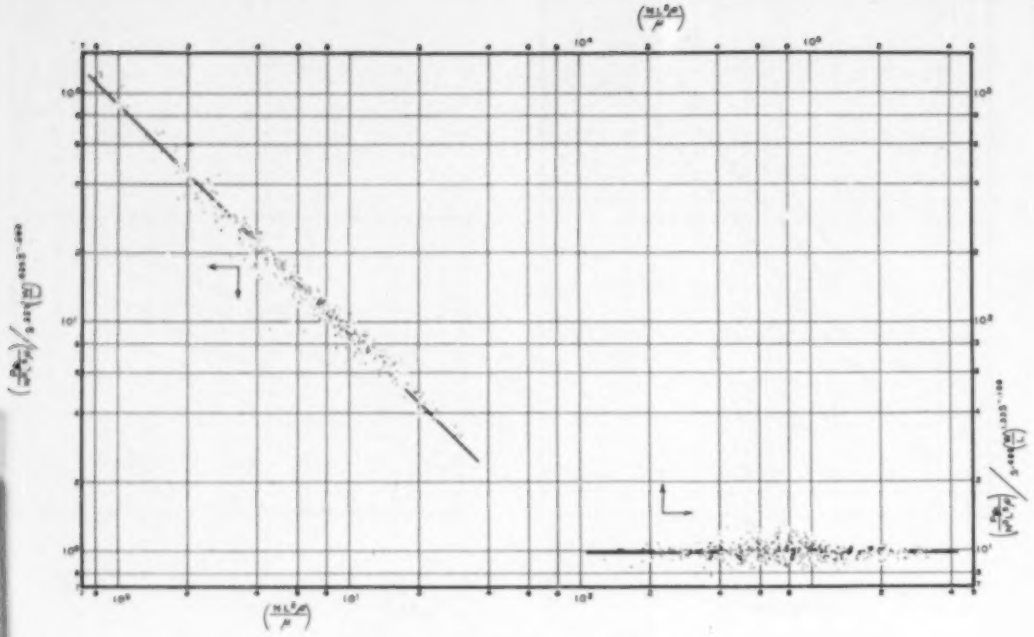

Fig. 6. Generalized Equations vs. Reynolds Number.

$$W = \frac{3}{12} = .25 \text{ ft.}$$

$$L = 2 \text{ ft.}$$

$$S = 4$$

then

$$\left(\frac{NL^2\rho}{\mu}\right)_{\text{transition}} = \frac{9.25}{(4)^{.200}}\left(\frac{.25}{2}\right)^{\left(\frac{.455}{(4)^{.200}} - \frac{1.55}{(4)^{.200}}\right)} = 32.2$$

Now, to test the Reynolds number of the above operating conditions,

$$N = \frac{60}{60} = 1.0 \text{ rev./sec.}$$

$$\rho = (.98)(62.5) = 61.3 \text{ lb. (mass)/(cu.ft.)}$$

$$\mu = (.000672)(30{,}000) = 20.16 \frac{\text{(lb. mass)}}{\text{(ft.)(sec.)}}$$

$$\frac{NL^2\rho}{\mu} = \frac{(1.0)(2)^2(61.3)}{20.16} = 12.16$$

Since this result is well below the value of 32.2, it may be assumed that viscous flow prevails.

(b) According to Equation (11)

$$Pg_c = 141N^{2.00}L^{5.00}W^{1.40}\mu$$

$$P = \frac{(141)(1.0)^2(2)^{5.00}(.25)^{1.40}(20.16)}{(32.2)}$$

$$= 277 \frac{\text{(ft.lb.)(force)}}{\text{sec.}}$$

$$P = .503 \text{ hp.}$$

Conclusions

1. Power consumption in the viscous and fully turbulent ranges has been correlated with operating conditions and with the principal dimensional measurements of turbines having two, four and six flat rectangular blades.

2. A method has been devised for estimating the point (Reynolds number) where the transition from viscous to turbulent flow may start, using the impeller dimensions and fluid properties as a basis.

3. The influence of dimensions and number of blades on the power consumption has been shown.

4. This work points the way for further similar investigation of other types of agitation impellers.

5. These factors may be used in the design of impellers or in changing the power consumption of existing impellers by modifying the dimensions.

Notation

b, b' = dimensionless group exponents
g = acceleration due to gravity, ft./(sec.)(sec.)
g_c = gravitational conversion factor, $\frac{\text{(ft.)(lb. mass)}}{\text{(sec.)(sec.)(lb. force)}}$
K, K' = equation coefficients
L = paddle length or diameter, ft.
N = angular velocity of impeller, rev./sec. or rev./min.
P = power consumed in agitation, ft. lb./sec.
S = number of impeller blades
W = paddle width, ft.
μ = viscosity, lb./(ft.)(sec.)
ρ = density, lb./cu.ft.

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METHOD AND CHART FOR NUMBER OF TRANSFER UNITS IN DIFFUSIONAL OPERATIONS

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For the rapid solution of design problems in diffusional operations, a chart is presented for obtaining numerical values of mean effective driving force, given only the terminal driving forces and the central driving force. The latter value may be replaced by a driving force located at a selected critical point.

To obtain the number of transfer units from the mean effective driving force, certain logarithmic correction terms are required. A nomograph is supplied to facilitate this step.

That portion of the equilibrium curve which is used in a given problem is regarded as an arc of a parabola, whose extension does not in general pass through the coordinate origin. If the used portion of the equilibrium cruve is irregular, the problem is separated into two or more steps. This procedure is equivalent to fitting two or more independent parabolic arcs to successive parts of the equilibrium curve.

The chart is based on the assumption of straight operating line, but its use may be extended to instances where the operating line is curved.

DESIGN calculations in diffusional operations involve determination of the number of transfer units (*3*), which in the general case is dependent upon a graphical integration. Several means of avoiding the graphical integration have been suggested. Some proposals employ alternate graphical constructions (*2, 11*); others present analytical solutions based on the assumption of specific geometrical forms of equilibrium and operating lines (*4-5, 7, 9*). The latter methods require preliminary calculation of parameters involving both coordinate axes of the equilibrium diagram.

It seemed apparent that it should be mathematically possible to derive expressions for mean effective driving force involving only the coordinate axis parallel to the driving forces, and that such expressions should be simpler to evaluate numerically. Further, expressions should be obtainable in which the mean effective driving force could be uniquely defined by one and only one value of driving force in addition to the terminal values. A most desirable form of expression would be one lending itself to the construction of a chart embodying all useful numerical solutions. Such a chart is here presented, together with a discussion of the derivations and calculations upon which it is based.

Equations for Mean Effective Driving Force

Derivation of Equations—Straight Operating Line. The relation of operating line to equilibrium curve in a diffusional operation is shown in Figure 1. The particular case used for discussion is that of absorption, and the particular unit of driving force employed is mole ratio in the gas phase. It is to be noted, however, that the equations and chart for mean effective driving force, as finally developed, will be applicable to any diffusional operation regardless of the units employed, if the operating line is straight and the equilibrium curve is of the form described here. It will be shown later that the equations and charts may be adapted to some cases involving curved operating lines.

The sole assumption is that, over the range pertinent to a given problem, the equilibrium curve may be represented within experimental error by a parabolic arc. The axis of the parabola is parallel to the driving forces. The prolongation of the arc does not necessarily pass through the coordinate origin.

This assumption is the same as that involved in the equations, charts, and nomographs of Scheibel and Othmer (*7, 9*), while Colburn (*3*) employs a combination of a parabolic arc in the rich region with a straight line in the dilute region.

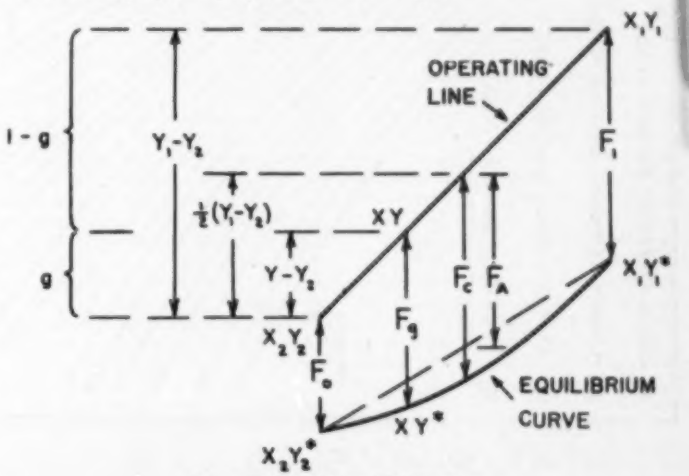

Fig. 1. Driving Force Relationships. Absorption diagram—Mole ratio units.

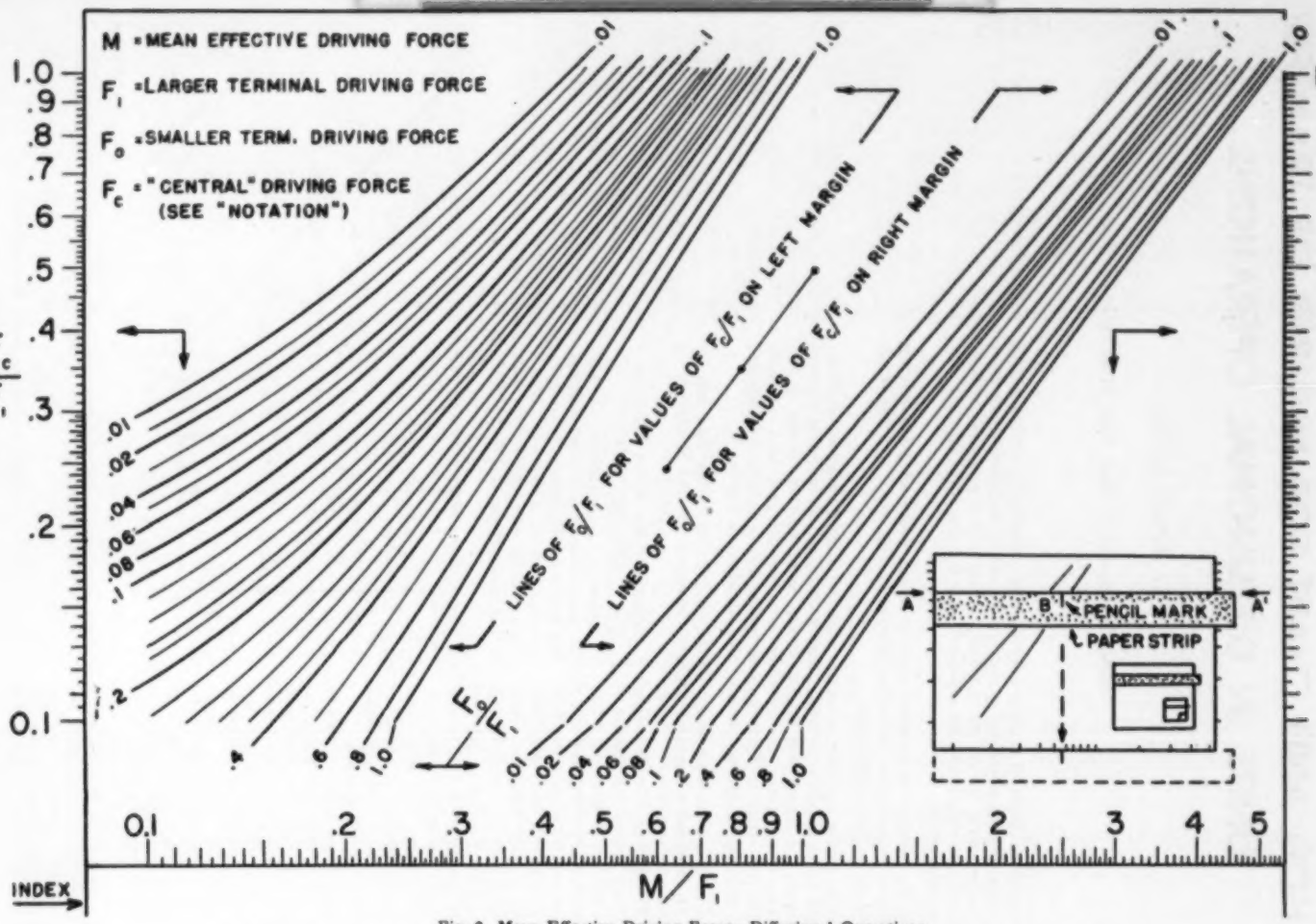
M = MEAN EFFECTIVE DRIVING FORCE
F1 = LARGER TERMINAL DRIVING FORCE
F0 = SMALLER TERM. DRIVING FORCE
Fc = "CENTRAL" DRIVING FORCE (SEE "NOTATION")
LINES OF F0/F1 FOR VALUES OF F0/F1 ON LEFT MARGIN
LINES OF F0/F1 FOR VALUES OF F0/F1 ON RIGHT MARGIN
F0/F1
PENCIL MARK
PAPER STRIP
INDEX
Fc/F1
M/F1

Fig. 2. Mean Effective Driving Force—Diffusional Operations.

For Straight Operating Line—Equilibrium data, between terminals only, fit some parabolic arc, whose extension need not pass through origin.

For Curved Operating Line—"Adjusted" equilibrium data meet the above requirement.

It should be emphasized that conformance to a parabolic arc is imposed only on the *pertinent* portion of the equilibrium curve, e.g., the portion directly beneath the operating line, in the instance where an absorption is evaluated in terms of over-all gas-phase driving forces. Further, since the extension of this arc need not pass through the coordinate origin, it may be chosen with any direction of curvature and any amount of curvature. The chosen arc is fixed by the end points of the pertinent portion of the equilibrium curve, and by a third point of correspondence freely selected anywhere between the two end points.

It will be demonstrated (e.g., numerical problem, Fig. 4) that the method may be extended to irregular equilibrium curves by separating the problem into two or more steps. Such procedure is equivalent to fitting two or more independent parabolic arcs to successive parts of the equilibrium curve. This device is also employed by Scheibel and Othmer (*7, 9*). Any physical system, however irregular its equilibrium curve, may thus be handled, at the cost of added steps. The time per step, with use of the numerical chart (Fig. 2), is short.

It can be shown that the divergence v of a parabolic arc from its chord, measured in a direction parallel to the axis of the parabola, is given by

$$v = 4g(1-g)v_{max} \qquad (1)$$

where g is the fraction of the linear distance from one end of the chord to the other, and v_{max} is the maximum divergence. It may be demonstrated that the latter occurs at the center of the chord.

Over-all driving forces in gas-phase units are denoted as indicated in Figure 1 and are defined as set forth in the Notation (*q.v.*).

The driving force F_g is equal to F_o plus a linear increment due to the divergence of the chord of the parabola from the operating line, plus the divergence of the parabola from its chord. Adding these three items, the general expression for driving force is

$$F_g = F_o + g(F_1 - F_o) + 4g(1-g)(F_C - F_A) \qquad (2a)$$

$$= F_o + (4F_C - 4F_A + F_1 - F_o)g + 4(F_A - F_C)g^2 \qquad (2b)$$

Defining M as the mean effective driving force in the expression

$$N_{OY} = \int_{Y_2}^{Y_1} dY/F_g$$

and noting that $dY = (Y_1 - Y_2)dg$

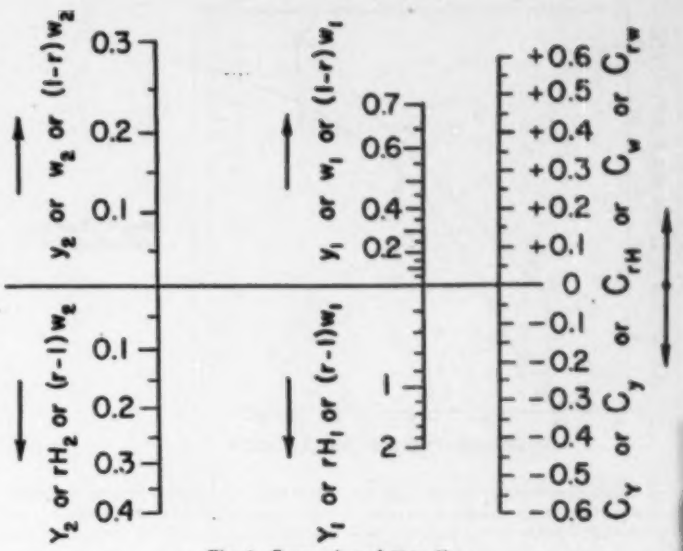

Fig. 3. Conversion of N to N_{OG}.

$$N_{OY} = \frac{Y_1 - Y_2}{M} = (Y_1 - Y_2)\int_0^1 \frac{dg}{F_g} \qquad (3)$$

Combining (*2b*) and (*3*), and integrating,

$$M = S/\left(\ln\frac{U+S}{U-S}\right) \qquad (4a)$$

where

$$S = \sqrt{U^2 - 4F_oF_1} \qquad (4b)$$

and

$$U = 2(2F_C - F_A) \qquad (4c)$$

or

$$M = S'/\left(2\arctan\frac{S'}{U}\right) \qquad (5a)$$

where

$$S' = \sqrt{4F_oF_1 - U^2} \qquad (5b)$$

Equations (*4a*) and (*5a*) are of the same form as those obtained by Scheibel and Othmer (*7*), a necessary consequence of the fact that the derivations have in common the assumption of the same form of equilibrium curve. The defining equations for U, S, and S' are, however, entirely different from those of Scheibel and Othmer. These quantities are defined herein wholly in terms of driving forces. They contain no element of that coordinate axis which is perpendicular to the driving forces, nor any element of reference to the coordinate origin.

For a given numerical computation, the choice between Equations (*4a*) and (*5a*) is dictated by the criterion of obtaining a real solution. It is found that when Equation (*4a*) is applicable, the equilibrium curve is concave towards the operating line, or is slightly convex toward it, the extent of the convex range depending on the ratio of F_o to F_1. When Equation (*5a*) is applicable, the equilibrium line is always convex toward the operating line.

If, as in desorption, it is elected to interpret all driving forces as negative numbers, the equations are still valid, and the value of M will be negative.

Application of Equations to Curved Operating Line. When an integral of the form $\int dY/F$ is graphically evaluated, the numerical result depends only upon the pairing of associated values of ordinate-of-operating-line versus ordinate-of-equilibrium curve. In the case of a curved operating line, if all (vertical) driving forces were shifted horizontally by amounts such that their upper ends formed a new straight "adjusted" operating line, then their lower ends would form a new adjusted equilibrium curve. No error would result if this new pair of adjusted lines were used to determine mean effective driving force (*8*).

The foregoing equations would then apply, if F_C were defined so as to fall in the proper place on the adjusted lines. The sole change would be that the assumption of parabolic form would then apply to the adjusted pertinent or used portion of the equilibrium curve rather than to the original. The definition of F_C (and F_g) in the Notation is framed in the proper manner, and may be used to yield a direct solution in conjunction with the chart to be presented. To obtain a solution, it is not essential actually to construct the adjusted equilibrium

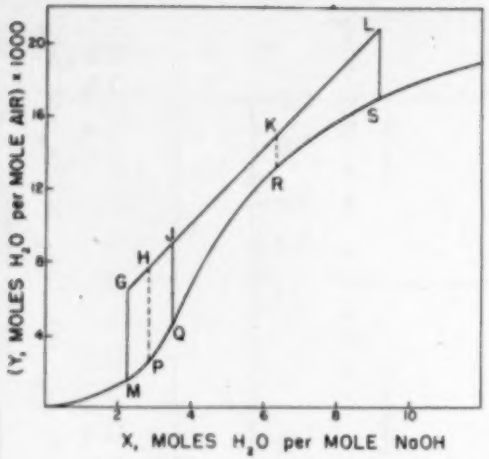

Fig. 4. Straight Operating Line.

line. Such construction serves only the purpose of checking visually the assumption of parabolicity of the adjusted pertinent or used portion of the equilibrium curve.

Form of Equations for Plotting. It is convenient to alter Equations (4*a*)-(5*b*) by substituting for $2F_A$ its equivalent $(F_0 + F_1)$, and dividing through by F_1. This yields

$$\frac{M}{F_1} = 2Q\Big/\left(\ln\frac{R+Q}{R-Q}\right) = Q/\text{arc tanh}\frac{Q}{R} \qquad (6a)$$

where

$$Q = \sqrt{R^2 - F_0/F_1} \qquad (6b)$$

and

$$R = \frac{2F_C}{F_1} - \frac{F_0}{2F_1} - \frac{1}{2} \qquad (6c)$$

or

$$\frac{M}{F_1} = Q'/\text{arc tan}\frac{Q'}{R} \qquad (7a)$$

where

$$Q' = \sqrt{F_0/F_1 - R^2} \qquad (7b)$$

If log (F_C/F_1) is plotted as ordinate against log (M/F_1) as abscissa, as in Figure 2, a family of lines of constant F_0/F_1 is obtained. These lines, over most of the useful range, are but slightly curved. Their spacing is roughly logarithmic and interpolation for intermediate values of F_0/F_1 is readily accomplished. The lines are comparatively steep, yielding well-defined values of M/F_1 for given values of F_C/F_1.

When the ratio Q/R approached unity, i.e., R nearly equal to Q, there was some difficulty in the numerical evaluation of Equation (6*a*). The range of available multiplace tables of hyperbolic tangent was exceeded, and it became necessary to use either an approximation formula of the type indicated by Scheibel and Othmer (*9*), or to employ the logarithmic form of Equation (6*a*) in conjunction with an electrical calculating machine. The latter procedure, which was adopted throughout, permitted the evaluation of R and Q to a precision sufficient to obtain $R - Q$ within 0.1% in all the calculations that were made. The full range of ten significant figures was necessary in some cases. In the evaluation of Equation (7*a*), care must be exercised to choose the proper value of this cyclic function.

All calculations were made in such a manner as to obtain a precision of 0.1% in the values of M/F_1, which is much better than can be reflected in a chart of the scale here presented in Figure 2. All values from all equations appear on this chart.

Relation of F_C to F_g. In some instances it may be desirable to employ, as a criterion of curvature of the equilibrium line, a driving force F_g in the critical part of the column where driving forces are small. The cognate value of F_C, for use in conjunction with Figure 2, will then be calculated from the parabola which has been defined by F_g and the terminal driving forces. The necessary relationship is obtained from Equation (2*a*) by substituting for $2F_A$ its equivalent $(F_0 + F_1)$, whence

$$\frac{F_C}{F_1} = \frac{1}{4g(1-g)}\left(\frac{F_g}{F_1}\right) - \frac{1-2g}{4g}\left(\frac{F_0}{F_1}\right) + \frac{1-2g}{4(1-g)} \qquad (8)$$

or specifically, when $g = 0.1$

$$\frac{F_C}{F_1} = 2.778\left(\frac{F_{0.1}}{F_1}\right) - 2\left(\frac{F_0}{F_1}\right) + 0.222 \qquad (9a)$$

or when

$$g = 1/6 = 0.167$$

$$\frac{F_C}{F_1} = 1.800\left(\frac{F_{0.167}}{F_1}\right) - \frac{F_0}{F_1} + 0.200 \qquad (9b)$$

or when

$$g = 1/4 = 0.25$$

$$\frac{F_C}{F_1} = 1.333\left(\frac{F_{0.25}}{F_1}\right) - \frac{1}{2}\left(\frac{F_0}{F_1}\right) + 0.167 \qquad (9c)$$

Use of Chart

Straight Operating Line. To evaluate mean effective driving force from the chart (Fig. 2), the only items required are the terminal driving forces and the central driving force.

1. Set slide rule at the reciprocal of F_1, and leave it there throughout the calculation. (e.g., set F_1 on C scale to right index of D scale)
2. Note from slide rule the values of F_0/F_1 and F_C/F_1 (e.g., opposite F_0 on C scale read F_C/F_1 on D scale).
3. As indicated in the chart inset, place a paper straightedge (cut or folded) so that its upper left corner A is on the left-hand scale at the figure sequence F_0/F_1. Adjust the straightedge so that it crosses the right-hand scale at the same figure sequence, at A'.
4. Selecting the proper group of lines of constant F_0/F_1, interpolate horizontally along the paper strip to the desired value of F_C/F_1 and make pencil mark B on the paper strip.
5. Move paper strip down to the horizontal scale for M/F_1 and read its value.
6. Read M from slide rule (e.g., opposite M/F_1 on D scale, read M on C scale).

It may be desired to force critical correspondence of the parabolic arc with the equilibrium data at some selected spot. In that event, omit evaluation of F_0 and evaluate in its stead the driving force F_g at any selected point on the operating line characterized by the fraction g. Use Equation (8), (9*a*), (9*b*), or (9*c*) to obtain the equivalent value of F_C/F_1. Proceed as in the numbered steps above.

Curved Operating Line. Some care is necessary to evaluate F_0 (or F_g) at the proper point on the operating line. For that point, the coordinate parallel to the driving forces is obtained by direct interpolation between terminal values, exactly as in the case of a straight operating line. The other coordinate may be calculated from the fact that, for single-component diffusion, the operating line becomes straight if converted to mole ratio or weight ratio units.

For example, if driving forces are in y units, and y_g is the interpolated value of the ordinate of the operating line at fraction g, algebraic solution yields

$$X_g = X_2 + (X_1 - X_2)(1 - y_1)\frac{g}{1 - y_g} \qquad (10a)$$

providing that the smaller terminal driving force (where $g = 0$) occurs at the lean end (subscript 2) of the tower, as is commonly the case. This type of calculation will be illustrated in a numerical problem. Values of X_1 and X_2 may be obtained from x_1 and x_2 and the value of X_g converted to the corresponding x_g.

In the event that the smaller terminal driving force occurs at the rich end, then

$$X_s = X_2 + (X_1 - X_2)\,(1 - y_1)\,\frac{1 - y_s}{1 - y_2} \tag{10b}$$

It is noted that only one intermediate point on the operating line need be located. It is not necessary to construct the adjusted equilibrium curve, provided that its pertinent or used portion is assumed to be an arc of parabolic form. This assumption is best checked, for a series of problems on a given physical system, by comparing the answer for a typical problem with that obtained from a graphical integration.

Format of Chart. The background grid of lines has been eliminated. Such a grid is objectionable from the standpoint of clarity of reproduction. Perhaps more important, it produces optical confusion in the operation of interpolating between successive lines of constant F_o/F_v. These lines, intersecting the edge of the separate paper strip, form a graduated scale of F_o/F_v for each selected value of F_o/F_v. This provides clear-cut interpolation of a type usually counted as one of the chief advantages of the nomographic form of presentation. All pencil marks are made on a disposable piece of paper. The edge of any ordinary piece of typewriter paper serves perfectly.

By suitable selection of scales, the reading precision of a rectangular coordinate chart may be made to reflect, throughout its range, the critical nature of the mathematical function upon which it is based. This is usually true of nomographs only in the middle of the range, precision decreasing toward the extremes as intersection angles become acute.

With reference to the type of chart herewith presented, a critical evaluation of manual and visual operations indicates that it is somewhat inferior to a single-operation nomograph if factors of speed, ease of use, and precision are all taken into account. On the other hand, it appears to be superior to a double-operation nomograph.

On the scale which can be printed in a space 7 by 10 in., results may be read from Figure 2 with an estimated precision of one per cent.

Calculation of Number of Transfer Units

Uncorrected Number of Transfer Units. In general, prior to correction, the number of transfer units is equal to the enrichment (expressed in the same units as the driving forces), divided by the mean effective driving force. Quantities N_{OT}, N_{Ov}, N_{Ou}, and N_{Ow} are defined in the Notation.

Corrected Number of Transfer Units. The correct number of over-all gas-phase transfer units N_{OG} is, in the case of distillation, numerically the same as the quantity here defined as N_{Ov} (although opposite in sign).

However, for single-component diffusion, e.g., absorption, the correction equations developed by Colburn (*5*) are employed.

$$N_{OG} = N_{OT} - \frac{1}{2}\,ln\,\frac{1 + Y_1}{1 + Y_2} = N_{OT} + C_T \tag{11}$$

$$N_{OG} = N_{Ov} + \frac{1}{2}\,ln\,\frac{1 - y_2}{1 - y_1} = N_{Ov} + C_v \tag{12}$$

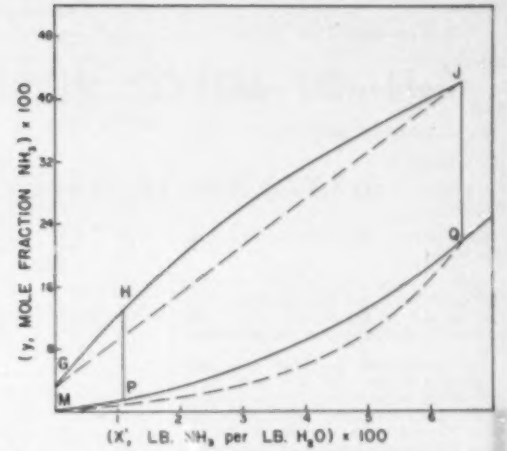

Fig. 5. Curved Operating Line.

$$N_{Ou} = N_{Ow} - \frac{1}{2}\,ln\,\frac{1 + rH_1}{1 + rH_2} = N_{Ow} + C_w \tag{13}$$

$$N_{Ou} = N_{Ow} + \frac{1}{2}\,ln\,\frac{1 - w_2}{1 - w_1} + \frac{1}{2}\,ln\,\frac{1 - (1 - r)w_2}{1 - (1 - r)w_1} = N_{Ow} + C_w + C_{rw} \tag{14*}$$

Equations (11)-(14) are written for cases analogous to absorption, i.e., for cases wherein the phase denoted by the concentration symbol is *losing* solute. If all equations (including defining equations for N in the notation table) are applied as they stand to cases analogous to desorption, the numerical values of N will all be correct but will be negative numbers (values of M will also be negative). This is a consequence of the fact that in desorption the phase denoted by the concentration symbol is *gaining* solute. It is somewhat confusing to handle separate complete sets of equations for desorption and absorption. This is readily avoided by applying all these equations as they stand to all cases, expecting all N values to be negative for cases analogous to desorption. By this procedure, the expressions for the logarithmic correction terms remain always the same.

Nomograph for Correction Terms. In Figure 3, a straight line through values of Y_1 and Y_2 indicates both the numerical value and the correct sign of C_T. When using this value in conjunction with Equation (11), note again that, in cases analogous to desorption, N_{OT} is a negative number.

Similarly, a straight line through y_1 and y_2 yields C_v. A straight line through rH_1 and rH_2 yields C_{rw}.

In correcting N_{Ou}, two correction terms must be obtained separately from the nomograph. A straight line through w_1 and w_2 yields C_w. If r is less than unity (as is common), a straight line through values of $(1 - r)w_2$ and $(1 - r)w_1$ yields C_{rw}. (In the event that r is greater than unity, a straight line through values of $(r - 1)w_2$ and $(r - 1)w_1$ yields C_{rw}.)

Solving by Tower Sections

When the used or pertinent portion of adjusted equilibrium curve cannot with sufficient accuracy be considered as parabolic over the entire range of the tower, the problem may be broken up into two or more appropriately selected sections, calculating values of N_{OG} for each section, and adding them. An example is shown in the following numerical problem, which is graphed in Figure 4.

In this manner, the chart may be employed in the solution of problems involving highly irregular equilibrium curves.

Numerical Examples

Straight Operating Line. This problem (*1*) illustrates also the method of solving by tower sections. The used portion of the equilibrium curve (Fig. 4) is obviously not a single parabolic arc.

"The water content of air, expressed as moles of water per mole of dry air, is reduced from 0.0209 to 0.00645 by countercurrent contact with NaOH solution entering at a concentration of 2.22 moles of water per mole NaOH, and leaving at 9.17 moles of water per mole of NaOH. Equilibrium data are given in mole ratio units. Assume isothermal operation, find N_{OG}."

In Figure 4, GL is the operating line and MS is the pertinent portion of the equilibrium curve. Choose the section boundary at the inflection point Q of the equilibrium curve, i.e., at $X = 2.86$. By interpolation, the corresponding ordinate of the operating line, at point J, is calculated as 0.0090.

Rich Section. JL is the operating line of this section and K is its midpoint. By interpolation between J and L, the coordinates of K are calculated as 6.33, 0.0150. Reading ordinates of Q, R, and S from the equilibrium curve, the driving forces are

$$QJ = F_1 = 0.0090 - 0.0046 = 0.0044$$

$$RK = F_2 = 0.0150 - 0.0034 = 0.0016$$

$$SL = F_s = 0.0209 - 0.01705 = 0.00385$$

* The last correction term in Equation (14), which was in error in the original article (*5*) and elsewhere (*7*), has been corrected by Colburn (*6*). In the original article, the proper value may be inserted in Equation (17), under Equation (36), and in the definitions of ϕ and ϕ' in the Notation. The entire term being commonly negligible in comparison with other terms in the equation, the revision is mainly one of academic interest.

Whence

$$F_e/F_1 = 0.875,\ F_c/F_1 = 0.364$$

and (Fig. 2)

$$M/F_1 = 0.510,\ M = 0.00225$$

Then

$$N_{oy} = (0.0209 - 0.0090)/0.00225 = 5.29$$

From Figure 3,

$C_Y = -0.01$, hence $N_{oo} = 5.28$ for rich section

Lean Section. Similarly $N_{oo} = 0.50$ for lean section.

Entire Tower. $N_{oo} = 5.78$. The last digit is, of course, not fully significant. Note that no part of Figure 4 is used in the numerical solution except the equilibrium line.

For comparison, graphical integration yields $N_{oo} = 5.66$. The 2% deviation is well within the probable experimental error of the equilibrium data. Equilibrium ordinates were given to the fourth decimal place, corresponding to errors of from 1 to 3% in driving forces, quite apart from the manipulative errors inherent in graphical integration.

Curved Operating Line. This problem illustrates also the use of F_g instead of F_o to produce critical correspondence of the equilibrium curve in the region of smallest driving forces.

"Air containing 42.2 per cent NH_3 by volume at 68° F. is scrubbed with water entering at 68° F. Exit air contains 3.2 per cent NH_3 by volume. Strong liquor contains 0.065 lb. NH_3 per lb. water. Using a calculated nonisothermal equilibrium curve (10), find N_{oo}."

In Figure 5, the solid line MPQ is the pertinent portion of the equilibrium curve and the solid line GHJ is the operating line. Choosing $g = 0.25$, the ordinate of point H is

$$y = 0.0032 + 0.25(0.422 - 0.032) = 0.130$$

and by Equation (10a), its abscissa is

$$X' = (0.065)(0.578)(0.25)/0.870 = 0.0108$$

Reading the ordinates of P and Q from the (true) equilibrium curve

$$QJ = F_1 = 0.422 - 0.218 = 0.204$$
$$MG = F_o = 0.032 - 0 = 0.032$$
$$PH = F_{o,m} = 0.130 - 0.015 = 0.115$$

whence

$$F_e/F_1 = 0.157,\ F_{o,m}/F_1 = 0.564$$

and from Equation (9c)

$$F_c/F_1 = 1.333(0.564) - 0.5(0.157) + 0.167 = 0.838$$

From Figure 2,

$$M/F_1 = 0.610$$

whence $M = 0.124$

$$N_{oy} = 0.390/0.124 = 3.14$$

From Figure 3, $C_y = 0.26$, whence $N_{oo} = 3.40$. No part of Figure 5 is necessary to the numerical solution except the equilibrium curve. The adjusted operating and equilibrium lines are indicated as broken lines.

For comparison, graphical integration yields $N_{oo} = 3.31$. The deviation of 3% is of the order of the error of the manipulations involved in the graphical integration.

Acknowledgments

The author is indebted to Kenneth Roach and Irwin Becker for the extensive machine calculations necessary to the preparation of the chart for mean driving force.

Notation

C_Y = correction term in Eq. (11)
C_y = correction term in Eq. (12)
C_{rH} = correction term in Eq. (13)
C_w = first correction term in Eq. (14)
C_{rw} = second correction term in Eq. (14)
F_0 = smaller of the two terminal driving forces, in any units dimensionally consistent with other quantities in the same calculation; may refer to either phase
F_1 = larger of the two terminal driving forces (not necessarily at the rich end of the column)
F_A = arithmetic average of F_0 and F_1
F_C = "central" driving force. For straight operating lines, evaluate at midpoint of operating line. For curved operating lines, if driving forces are expressed in ordinate units, evaluate at that point of the operating line whose ordinate is the average of the terminal operating ordinates; conversely, if forces are in abscissa units, evaluate at that point of the operating line whose abscissa is the average of the terminal operating abscissae
F_g = driving force at a point on the operating line characterized by the fraction g. The coordinate used in calculating g must be the one corresponding to the units in which driving forces are expressed
g = fraction denoting position of a point on the operating line in terms of *one* selected coordinate, the interval between operating terminals in that coordinate being taken as unity. At the terminal characterized by the driving force F_0, $g = 0$
M = mean effective driving force; subscript y, Y, H, or w indicates units in which measured
N_{OG} = number (corrected) of over-all transfer units, based on gas phase

$$N_{OY} = \int_{Y_2}^{Y_1} dY/(Y - Y^*) = (Y_1 - Y_2)/M_Y$$

$$N_{oy} = \int_{y_2}^{y_1} dy/(y - y^*) = (y_1 - y_2)/M_y$$

$$N_{oH} = \int_{H_2}^{H_1} dH/(H - H^*) = (H_1 - H_2)/M_H$$

$$N_{ow} = \int_{w_2}^{w_1} dw/(w - w^*) = (w_1 - w_2)/M_w$$

r = ratio of molecular weight of solute-free stream to that of solute
$w = H/(1 + H)$ = weight fraction of solute in stream
$x = X/(1 + X)$ = mole fraction of solute in liquor
$X = x/(1 - x)$ = mole ratio of solute to solvent
X' = alternate symbol for H when applied to liquid phase
$y = Y/(1 + Y)$ = mole fraction of solute in gas
$Y = y/(1 - y)$ = mole ratio of solute to carrier gas
$H = w/(1 - w)$ = weight ratio of solute to solute-free stream

Subscripts:

1 refers to solute concentrations at rich end of column
2 refers to solute concentrations at lean end of column

Superscript:

* designates equilibrium value corresponding to (unstarred) value of concentration on conjugate coordinate axis

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THERMODYNAMIC DATA FOR SYSTEM SO_2-H_2O

BIBLIOGRAPHY AND CRITICAL ANALYSIS

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An exhaustive literature survey was made to locate equilibrium solubility-vapor pressure data for the system sulfur dioxide-water. (SO_2-H_2O). Data so obtained are statistically correlated for SO_2 concentrations of 0.03 to 10.0 g. SO_2/100 g. H_2O and at temperatures of 0° to 130° C. The correlated results are presented as straight lines on an Othmer-Cox-type chart by modifying the ordinate. Slopes and intercepts are also presented at all SO_2 concentrations for the linear equation $\log_{10} P_m = b \log_{10} p_w + a$ relating the variables.

Use of the Othmer method for this system is discussed. Heat effects calculated from the vapor-pressure curves are compared with those reported in the literature as independent determinations of heats of solution. The paucity of data above 130° C. is demonstrated and suggestions made for further investigation in this region.

A similarity of this system with seven other weak electrolytes is exhibited from changes in the first ionization constant with temperature.

SURVEY of the literature on the equilibrium vapor pressure exerted by the system SO_2–H_2O reveals certain disagreement among investigators and emphasizes the absence of data at elevated temperatures (above 130° C.). The primary purposes of this paper are (1) to collect and correlate the available data by a rigorous statistical method and (2) to present the result in the form of an Othmer-Cox-type chart. Secondary purposes are (1) to compare heats of solution calculated from the equilibrium vapor pressures with experimental determinations reported in the literature, (2) to extend the vapor-pressure lines into the critical region to demonstrate the lack of data on the system under those conditions, (3) to discuss the constancy of the heat-effect ratio on the Othmer-Cox chart and finally (4) to point out a similarity in this system with other weak electrolytes as shown by changes in equilibrium constants with temperature.

Measurements of the equilibrium vapor pressure and composition of sulfurous acid solutions (*18, 21, 30, 37, 42, 54, 58, 63, 64, 68*) between 1850 and 1925 are reported by Fulda (*22*), Seidell (*60*), Haslam et al (*26*), Sherwood (*62*), Campbell (*5*) and The International Critical Tables (*31*). Between 1925 and 1935 Campbell (*5*), Maass and co-workers (*7, 24, 39, 41*), Conrad and Beuschlein (*2*) and Johnstone and Leppla (*32*) extended knowledge of this system between 0° C. and 130° C. and down to low partial pressures of SO_2. Davis (*12, 13*) also prepared nomographs and equations representing data reported earlier (*7, 39, 62*).

Discrepancies between the graphical and tabulated data of Sherwood (*62*) were discovered in this survey. Appropriate corrections are to be made in the forthcoming 3rd edition of Perry's handbook. However, the Davis (*12*) nomograph and equation based on the erroneous data give results more than 60% off at 40° C.

Since 1935 Wickert (*71*), Otuka (*50*), Kuznetsov (*35*), Beuschlein and Simenson (*3*), Braun (*4*) and White, Vivian and Whitney (*69*) have published data between 2° C. and 150° C. Unfortunately, data of Otuka at 150° C. were not available at the writing of this survey. Davis (*14-16*) devised nomographs and equations representing previous data (*3, 32*). Republished data (*8, 31, 62*) were presented by Beuschlein and Conrad (*2*) and Perry (*51*); Othmer and White (*49*) use these data from Perry in graphical form. Lundberg (*38*) reproduces graphically vapor pressure-solubility data for this system but gives no source.

Vapor-Pressure Data Correlated. No effort was made to correlate data in the literature before the summary of Sherwood (*62*) with the exception of that reported by Oman (*42*), Enckell (*18*) and Smith and Parkhurst (*64*) which were readily available. The summarized data (*31*) and the values calculated by Campbell (*5*) from the results of Hudson (*30*) were considered along with those of Sherwood although some early investigations were included in more than one of these reviews. This was done primarily to compare these summaries with data taken in the last quarter century for they are not so far removed in the literature that present-day utilization is unlikely.

In addition, experimental data reported by investigators (*2, 7, 24, 32, 39, 41, 69*) between 1925 and 1948 were included in the statistical treatment. Data of Beuschlein and Simenson (*3*) were treated separately because of internal inconsistencies which prohibited reliable interpolation to concentrations other than those reported.

Method of Correlation. Texts on thermodynamics and physical chemistry recommend Duhring's rule and the integrated Clausius-Clapeyron equation in approximate form to correlate vapor pressure-temperature data for a wide variety of substances. Conrad and Beuschlein (*8*) use the Duhring relation to plot vapor-pressure data for the system CaO–SO_2–H_2O at 15° and 25° C. and to extrapolate (*9*) to temperatures of 5°, 35°, 50°, and 60° C. The method chosen for this study, however, is one first suggested by Cox (*11*) and developed by Othmer (*44*) and coworkers (*44-49*) to correlate many physical properties of pure and mixed chemical substances. The Othmer method was used successfully by Whitwell and Toner (*70*) to correlate vapor pressures of water adsorbed on textile fibers. Othmer writes the Clausius-Clapeyron equation in the differential

TABLE 1

The Slopes, Correlation Coefficients and Sample Size for Individual Investigators

Investigator No. / Mol. Concentration SO_2	2	3	5	7	17	23	30	31	39	40	41	51	53	58
							SLOPES - "b"							
0.03	-	-	-	-	-	-	-	0.9953	-	-	-	0.9951	-	-
0.05	-	-	-	-	-	-	-	0.9967	-	-	-	0.9707	-	-
0.08	-	-	-	-	-	-	-	0.9939	-	-	-	0.9789	-	-
0.10	-	-	-	-	-	-	-	0.9795	-	-	-	0.9878	-	-
0.15	-	-	-	-	-	-	-	0.9795	-	-	-	0.9878	-	-
0.25	-	-	-	-	-	-	-	*	-	-	-	0.9925	-	-
0.50	*	-	0.7056	0.6960	*	-	0.6395	-	-	0.8423	0.8168	0.8321	0.7953	0.8066
0.75	-	0.8603	-	-	-	-	-	-	-	-	-	-	-	-
1.00	*	-	0.5711	0.5739	0.6538	0.7105	0.7553	-	-	0.7330	0.7863	0.7999	0.8187	0.7956
1.50	-	0.7351	-	-	-	-	-	-	-	-	-	-	-	-
2.00	*	-	0.5088	0.4889	0.7297	0.6805	0.6759	-	-	0.7038	0.6854	0.6439	0.6953	0.6570
3.00	*	-	0.5388	0.5198	0.7883	0.6309	0.6357	-	-	0.6917	0.6755	0.6567	0.6696	0.6429
4.00	*	-	0.5345	0.6035	*	0.5969	0.6071	-	-	0.7039	0.6570	0.6436	0.6553	0.6666
5.00	-	0.6093	-	-	-	-	-	-	-	-	-	-	-	-
6.00	*	-	0.5333	0.5000	*	0.5753	0.6275	-	-	0.6884	0.6567	0.6257	0.6408	0.6408
8.00	*	-	0.5890	0.5795	*	0.5815	0.6263	-	-	0.7038	0.6416	0.6287	0.6362	0.6261
9.95	-	0.5438	-	-	-	-	-	-	-	-	-	-	-	-
10.00	*	-	0.5390	0.5535	-	-	0.6401	-	-	0.7089	0.6553	*	0.6810	0.6438
15.00	*	-	0.5651	-	-	-	0.5987	-	-	0.6385	0.6218	*	0.6148	0.5854
							- CORRELATION COEFFICIENTS -							
0.03	-	-	-	-	-	-	-	1.0000	-	-	-	1.0000	-	-
0.05	-	-	-	-	-	-	-	1.0000	-	-	-	1.0000	-	-
0.08	-	-	-	-	-	-	-	1.0000	-	-	-	1.0000	-	-
0.10	-	-	-	-	-	-	-	1.0000	-	-	-	1.0000	-	-
0.15	-	-	-	-	-	-	-	*	-	-	-	1.0000	-	-
0.25	-	-	-	-	-	-	-	*	-	-	-	1.0000	-	-
0.50	*	-	0.9954	0.9999	*	-	0.9997	-	-	0.9997	0.9995	0.9999	0.9999	1.0000
0.75	-	0.9999	-	-	-	-	-	-	-	-	-	-	-	-
1.00	*	-	0.9991	0.9991	1.0000	0.9999	0.9996	-	-	0.9994	0.9984	0.9993	1.0000	0.9994
1.50	-	0.9995	-	-	-	-	-	-	-	-	-	-	-	-
2.00	*	-	0.9998	0.9999	1.0000	1.0000	0.9995	-	0.9984	1.0000	0.9981	0.9994	0.9998	0.9999
3.00	*	-	0.9998	0.9998	1.0000	0.9995	1.0000	-	0.9982	1.0000	0.9993	0.9991	0.9996	0.9998
4.00	*	-	0.9998	0.9999	*	0.9998	0.9999	-	0.9992	0.9996	1.0000	0.9984	0.9998	0.9998
5.00	-	0.9998	-	-	-	-	-	-	-	-	-	-	-	-
6.00	*	-	0.9997	0.9998	*	0.9998	0.9997	-	0.9996	1.0000	1.0000	0.9993	0.9999	0.9998
8.00	*	-	0.9998	0.9997	*	0.9996	0.9998	-	0.9998	1.0000	1.0000	0.9996	1.0000	0.9996
9.95	-	0.9993	-	-	-	-	-	-	-	-	-	-	-	-
10.00	*	-	0.9986	0.9996	-	-	0.9998	-	0.9998	0.9999	*	0.9998	1.0000	0.9998
15.00	-	-	0.9998	-	-	-	1.0000	-	0.9994	1.0000	*	0.9997	1.0000	0.9997
							- SAMPLE SIZE (Number of data points) -							
0.03	*	-	-	-	-	-	-	3	-	-	-	6	-	-
0.05	*	-	-	-	-	-	-	3	-	-	-	6	-	-
0.08	*	-	-	-	-	-	-	3	-	-	-	6	-	-
0.10	*	-	-	-	-	-	-	3	-	-	-	6	-	-
0.15	*	-	-	-	-	-	-	3	-	-	-	6	-	-
0.25	*	-	-	-	-	-	-	*	-	-	-	6	-	-
0.50	3	-	9	11	3	-	11	-	-	6	7	8	6	6
0.75	-	13	-	-	-	-	-	-	-	-	-	-	-	-
1.00	3	-	9	11	3	6	11	-	-	6	7	8	6	6
1.50	-	13	-	-	-	-	-	-	-	-	-	-	-	-
2.00	3	-	9	11	3	6	11	-	-	6	7	8	6	6
3.00	3	-	9	11	3	6	5	-	-	5	6	8	6	6
4.00	3	-	9	10	3	6	5	-	-	5	6	8	6	6
5.00	-	11	-	-	-	-	-	-	-	-	-	-	-	-
6.00	3	-	7	10	3	6	6	-	-	5	6	8	6	6
8.00	3	-	7	9	3	6	6	-	-	5	6	8	6	6
9.95	-	10	-	-	-	-	-	-	-	-	-	-	-	-
10.00	3	-	6	8	-	-	3	-	-	5	6	8	6	6
15.00	-	-	6	-	-	-	2	-	-	5	6	8	6	6

* - Sample size of one
- - No data at this concentration

approximate form for each of the systems in question, SO_2–H_2O and a reference material, in this case, water. For SO_2—H_2O

$$d\ln p_s = \frac{\Delta H_s dT}{RT^2} \qquad (1)$$

where ΔH_s is the molal heat of solution of gaseous SO_2 in liquid water at temperature $T°$ K.

For water

$$d\ln p_w = \frac{\lambda_w dT}{RT^2} \qquad (2)$$

where λ_w is the molal latent heat of vaporization at temperature $T°$ K. Dividing Equation (1) by (2)

$$\frac{d\ln p_s}{d\ln p_w} = \frac{\Delta H_s}{\lambda_w} \qquad (3)$$

Integrating

$$\ln p_s = \left(\frac{\Delta H_s}{\lambda_w}\right) \ln p_w + C \qquad (4)$$

which says that the vapor pressure of SO_2, p_s, plotted on logarithmic paper against the vapor pressure of water, p_w, at the same temperature should yield a straight line if the slope $(\Delta H_s/\lambda_w)$ is independent of temperature. It is a virtue of the Othmer method that the quantity $(\Delta H_s/\lambda_w)$ is less dependent on temperature than ΔH_s or λ_w considered separately. However, it will be shown subsequently that at least for pure SO_2, $(\Delta H/\lambda)$ is by no means constant and that the straight lines obtained on the Othmer-Cox chart are the result of deviations from the perfect gas laws and the relatively large ratio of liquid to gas volume at equilibrium.

Othmer and White (*49*) plotted values of p_s by Equation (4) at temperatures below 100° C. Two characteristics of the lines were evident, namely, (1) they were "straight within experimental error" and (2) the slopes at different liquid phase SO_2 concentrations were essentially constant, unlike other systems similarly plotted.

Attempts were made to use Equation (4) for the present study but in many cases curved lines were obtained, particularly at low concentrations and at temperatures above 100° C. Indeed, examination of the lines of Othmer and White reveals a slight curvature at lower SO_2 concentrations, even below 100° C. Therefore, the Othmer treatment of this system was modified by using the total pressure exerted by the system, $p_s + p_w = P_m$ rather than the vapor pressure, p_w, of SO_2 only. Equation (4) then becomes

$$\log_{10} P_m = \left(\frac{\Delta H_m}{\lambda_w}\right) \log_{10} p_w + C' \qquad (5)$$

where ΔH_m is the heat of solution of an average mixed mole of SO_2 and H_2O vapor. The change in logarithm base was only for convenience. Data of all investigators plotted according to Equation (5) gave straight lines over the entire temperature range studied. Furthermore, the slopes $(\Delta H_m/\lambda_w)$ of the lines decreased with increasing liquid phase SO_2 concentration as they should since the molal heat of solution normally decreases as solute concentration increases.

In spite of a high degree of linearity for each, the slope from investigator to investigator varied considerably in no readily detectable pattern. Some method was sought, therefore, which would permit rigorous evaluation of the data from each source and calculation of a soundly weighted average from several independent contributors.

Statistical Treatment of Data

Analysis of covariance according to Snedecor (*65*) was used for treatment of the data.

Values of P_m and p_w at the constant "*S*" values of Table 1 were carefully interpolated from the reported data and logarithms of these were considered the dependent and independent variables, respectively, in the statistical analysis.

Investigators were treated separately at first by the theory of least squares to obtain correlation coefficients and slopes at all *S* values considered. Table 1 shows the results. The individual correlation coefficients are uniformly high, indicating a high degree of consistency for each set of data at a constant SO_2 concentration. Low sample size in several cases results in high correlation coefficients. However, the individual slopes vary considerably resulting, therefore, in disagreement among investigators at various temperature levels depending on the slope magnitudes.

Data of all investigators at constant SO_2 concentrations were next subjected to analysis of covariance. Significance tests were applied to the results and investigators differing most from the group were eliminated until significance at the 5 per cent level was attained. Investigators retained as well as over-all slopes and intercepts of the lines best representing all the data treated are shown in Table 2. The lines are plotted on Figure 1 and are offered as the

most reliable vapor pressure data available at this time for the system SO_2–H_2O at temperatures up to 130° C.

Discussion of Correlated Data

Data of the investigators listed in Table 1 but not in Table 2 were discarded in the statistical treatment of the vapor-pressure data. Evidently, these were not necessarily the same investigators at each SO_2 concentration. Data of Campbell (*5*) calculated to temperatures of 90° C. from the original data of Sims (*63*) and Hudson (*30*) deviated so widely they were discarded at all SO_2 concentrations. Calculated data cannot be expected to agree closely with experimentally determined values because of the following: (a) the activity coefficients of the H^+ and HSO_3^- ions are less than unity and depend on the SO_2 concentration *S* (*32*) under these conditions, (b) the heat effect is not independent of temperature as assumed and (c) use of the approximate Clausius-Clapeyron equation introduces errors.

Examination of the slopes for individual investigators will reveal that those for Beuschlein and Simenson (*3*), although in general agreement at low SO_2 concentrations, differ markedly at the higher SO_2 concentrations. In spite of this, these data would have been considered for the statistical treatment had it been possible to interpolate accurately to SO_2 concentrations other than those reported.

Data of Enckell (*18*) and Beuschlein and Conrad (*2*) were considered but because of low sample size their effect would not have been felt in the statistical calculations. Data of White, Vivian and Whitney (*69*), Morgan and Maass (*41*), and (*31*) were used at all concentrations. Values of Sherwood (*62*) and Oman (*42*) were discarded at only two concentrations, Gurd, Gishler and Maass (*24*) at three and all others at four or more concentrations. No attempt is made in this paper to locate the causes for deviations of the individual experimental data from the statistically determined best lines of Figure 1. However, an analysis of the factors involved is given in the following section.

Comparison of Calculated and Observed Heats of Solution

According to Equation (5), the slopes of the lines on Figure 1 should be equal to $\Delta H_w/\lambda_w$. These slopes, furthermore, evidently lie between the values of unity, for pure H_2O and 0.57 for pure SO_2. It appears simple, therefore, to calculate the molal heat of solution of an average mixed mole of SO_2 gas and H_2O vapor in aqueous solutions of SO_2, since reliable values of λ_w are commonplace. It is not simple as suggested by lack of agreement of the literature values of λ_s/λ_w for pure SO_2 with the slope of the corresponding line of Figure 1 which is a plot of the vapor-pressure data of Rynning and Hurd (*57*) and Lange (*36*). To understand the troubles met in this case, and likely to be met when considering the mixture, basic quantities involved in the slope of the line must be examined more closely.

The Clausius-Clapeyron equation in exact form for pure SO_2 is

$$\frac{dp}{dT} = \frac{\lambda_s}{T\Delta V} = \frac{\lambda_s}{T(V_g - V_l)} \quad (6)$$

where V_g and V_l are molal gas and liquid volumes, respectively and λ_s is the molal latent heat of vaporization for SO_2. Instead of substituting the perfect gas law and neglecting V_l with respect to V_g as is usually done, the following equations:

$$V_g = Z_s RT/p \quad (7)$$

$$k_s = (V_g - V_l)/V_g \quad (8)$$

substituted in Equation (6) give

$$\frac{d\ln p}{dT} = \frac{\lambda_s}{k_s Z_s RT^2} \quad (9)$$

where Z_s is the compressibility factor. Combined with the similar equation for water and integrated there is obtained

$$\log p_s = \left(\frac{\lambda_s}{\lambda_w}\right)\left(\frac{k_w}{k_s}\right)\left(\frac{Z_w}{Z_s}\right) \log p_w + C'' \quad (10)$$

and the slope now comprises not only heat effects but also properties of state of both gas and liquid phases. Thermodynamic data for pure SO_2 are available in the literature (*22, 25, 27, 29, 40, 54, 57*) but those of Rynning and Hurd (*57*) are the most recent. Utilizing these to calculate λ_s, k_s and Z_s for pure SO_2 and data from steam tables to compute the same quantities for pure water, the variations in the three ratios of the slope are found to be $\lambda_s/\lambda_w = 0.537$ to 0.398; $k_w/k_s = 1.004$ to 1.083; and $Z_w/Z_s = 1.036$ to 1.332 over the temperature range of 4° to 104° C. Multiplying these three quantities together at each of several temperatures in this range reveals that the slope, 0.57, of the pure SO_2 line, which is exceptionally linear to the critical temperature, can be calculated to within 0.6 per cent.

This result emphasizes that equilibrium vapor-pressure data can never be extrapolated with accuracy using a single pressure determination and a heat of solution at one temperature unless

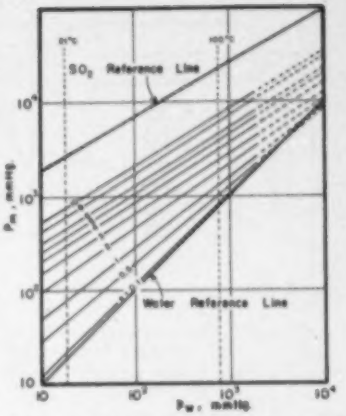

Fig. 1. Modified Othmer-Cox chart showing equilibrium solubility—vapor pressure relationship for system SO_2-H_2O.

(1) the temperature and known equilibrium pressure are at a level where deviations from the perfect gas law are small and V_l/V_g is vanishingly small relative to unity or (*2*) thermodynamic data for the vapor mixture and density data for the liquid phase are available over the entire temperature range. It appears, therefore, that experimental determination of vapor pressures over wide ranges of temperature is preferable regardless of time and effort consumed. However, heat of solution data are available in the literature for the system SO_2–H_2O at temperatures where perfect gas laws are normally applicable and liquid volumes are negligible. It is proposed to compare the reported heats of solution with those calculated from the vapor-pressure lines to ascertain: (1) the precision of calculating vapor pressures of aqueous SO_2 solutions at temperatures other than that at which equilibrium vapor pressures and heats of solution are known and (*2*) whether independent heat-effect data determined experimentally can be used to appraise the reliability of vapor pressure-solubility data in the literature.

TABLE 2

Values of a_0 and a_1 of the Equation $\log_{10} P_s = a \log_{10} P_w + a$ as Determined by Statistical Treatment of Data from Several Investigators.

SO_2 Concentration gms. SO_2/100 gms. H_2O	Investigators Retained	Overall Slope, a_1	Overall Intercept, a_0
0.03	51, 61	0.9865	0.0536
0.05	51, 61	0.9805	0.0567
0.08	51, 61	0.9751	0.0842
0.10	51, 61	0.9681	0.1091
0.15	51, 61	0.9518	0.1704
0.50	7, 30, 40, 41, 61, 68	0.8282	0.6160
1.00	7, 23, 30, 40, 41, 61, 68	0.7660	0.9240
2.00	7, 23, 30, 40, 41, 61, 63, 68	0.6832	1.2992
3.00	23, 30, 40, 41, 61, 68	0.6473	1.5135
4.00	30, 40, 41, 61, 68	0.6318	1.6668
5.00	30, 40, 41, 63, 68	0.6356	1.7596
6.00	30, 38, 40, 41, 61, 63, 68	0.6260	1.8537
8.00	30, 38, 40, 63, 68	0.6296	1.9863
10.00	30, 38, 40, 61, 63, 68	0.6183	2.0944

TABLE 3

Comparison of Heats of Solution Calculated from Roth (56) and Values of H_s Given in Table II

SO_2 Concentration gm. SO_2/ 100 gm. H_2O	Heat of Solution from Roth (56) at 21° C. cals./mol SO_2	Calculated* Heat of Solution, ΔH_m from Roth cals./gm. mol mixture	Calculated* Heat of Solution from H_s values of Table II cals./gm. mol mixture	Difference %
0.05	10,960	10,597	10,560	3.38
0.08	9,980	10,447	10,336	3.56
0.10	9,304	10,409	10,281	3.25
0.20	9,210	10,348	10,208	3.37
0.35	8,930	10,176	10,076	3.30
0.50	8,680	9,974	9,733	3.99
1.00	7,795	9,460	8,853	6.95
2.00	7,375	7,761	7,256	6.51
3.00	7,170	7,460	6,825	9.30
4.00	7,050	7,255	6,588	9.68
5.00	6,950	7,093	6,504	9.05
6.50	6,900	7,052	6,501	8.45
8.00	6,900	6,955	6,506	6.37
10.00	6,750	6,826	6,519	4.71

* Latent heat of water at 21°C. = 10,544 cals./mol.

Differential heats of solution for SO_2 in H_2O have been determined by Stiles and Felsing (*67*) at 25° C., Ramstetter and Hantke (*53*) at 20° C. and Roth (*56*) and a co-worker at 21° C. For SO_2 in H_2SO_4, heats of solution are reported by Kurin (*34*). Except in dilute solutions the data of Stiles and Felsing and Roth, et al. are in good agreement, whereas, the data of Ramstetter and Hantke are much higher than that of the latter two. Since Roth made measurements over wider ranges in concentration his data at 21° C. (which are reproduced in Table 3) were compared with the heats of solution computed from the slope and intercept values of Table 2.

Equations of the lines on Figure 1 are of the form

$$y = bx + a \qquad (11)$$

where $y = \log P_m$; $x = \log p_w$; $b =$ slope and $a =$ intercept. To illustrate the method of calculating the total molal heat of solution of an average mixed mole of SO_2 and H_2O vapor, data of $S = 1.00$ g. $SO_2/100$ g. H_2O will be considered. At 21° C., the value of $p_w = 18.65$ mm. H_g and $x = 1.2707$. For $S = 1.00$, $b = 0.7600$ and $a = 0.9240$. From Equation (11), $y = 1.8897$ and $P_m = 77.57$. The vapor pressure of SO_2 then is $P_m - p_w = p_s = 58.92$. Values of n_s and n_w, the mole fractions of SO_2 and H_2O, respectively, in the vapor phase are $p_s/P_m = 0.760$ and $p_w/P_m = 0.240$. Considering these values as the SO_2 and H_2O content of the average mixed mole, the total heat effect upon solution is

$$(0.760)(7735) + (0.240)(10{,}544)$$

$$= 8410 \text{ cal./mole}$$

where 7735 is the molal heat of solution for SO_2 from Roth (*56*) and 10,544 is the latent heat of vaporization for water at 21° C. The comparable value from the slope of the vapor pressure lines was calculated to be 8013 cal./mole by multiplying $\Delta H_m/\lambda_w = b = 0.7600$ by $\lambda_w = 10{,}544$. Corresponding values for all concentrations considered are tabulated in Table 3.

Differences between these two heats of solution do not appear great. Expressed as percentages based on the value derived from vapor pressures, the maximum difference is 9.3% and the minimum 1.2%. However, it is easily shown from the equation

$$\frac{dP_m}{P_m} = (\log p_w)db + da \qquad (12)$$

that extrapolation of the vapor pressure line for $S = 3.0$ from 21° to 100° C. using the slope calculated from the Roth heats of solution, gives a result at the higher temperature 25% above the vapor pressure read from Figure 1. This is the worst case. The best would be for $S = 0.03$, in which case a difference of only 1.2% in heat effect leads to an error of 4.5% in the extrapolated vapor pressure at 100° C. Evidently, extrapolation to higher temperatures in either of these cases leads to errors greater than 4.5 and 25 per cent.

Reasons underlying these differences in heat effects here calculated are not evident. If it be assumed the perfect gas law is not applicable even at 21° C. and a pressure below atmospheric for the mixture of gases, it appears that $\bar{Z}_w/\bar{Z}_m$ would be greater than unity. This would amplify the differences. In fact, Maass and co-workers (*10, 66*) report apparent molecular weights of gaseous SO_2 at 25° C. to be somewhat greater than 64.06, the accepted value, upon which heats of solution reported are probably based. This means the heat of solution of an average mixed mole of SO_2 and H_2O as calculated from the data of Roth are probably slightly low or, in other words, the differences in the two heat effects considered are probably greater than calculated. Furthermore, at this temperature and pressure (k_w/k_m) is close to unity and thus would have no influence on the discrepancies. Consideration was given to the effect of heats of hydration and ionization on the thermodynamic derivation of the Clausius-Clapeyron equation and it was concluded that the derivation is independent of the working substances and the total heat effect involved as long as reversible, cyclical processes are assumed. Even if these heat effects are deducted from the total the differences found here are exceeded in the reverse direction.

Although a plot of log p_s versus log p_w gave a curved line, the possibility was considered that the slope of the tangent to the line at 21° C. and the slope calculated from Roth's data would be in better agreement. From Equation (11) it may be shown that if

$$\log (P_m - p_w) = u = f(x)$$

$$= f(\log p_w) \qquad (13)$$

the equation of the line u vs. x is

$$u = x + \log [(A)(10)^{(b-1)(x)} - 1] \qquad (14)$$

where $A =$ anti log a. Then the slope at any point is

$$\frac{du}{dx} = 1 + \frac{A(b-1)}{A - 10^{(1-b)x}} \qquad (15)$$

Values of du/dx at 21° C. obtained from this equation are tabulated in Table 4. The heat effects calculated from Roth's data, assuming in this case, solution of one mole of SO_2 only in aqueous SO_2 solution, are presented also in Table 4 along with the heats of solution calculated from values of du/dx and the latent heat λ_w. Evidently, the agreement is poorer, in some cases very much so, than that attained by plotting log P_m versus log p_w.

It appears then that extrapolation of vapor-pressure curves for the system SO_2-H_2O, using either vapor pressures of SO_2 or total pressures and available heats of solution at one temperature, is unwise where precise results at other temperatures are desired.

TABLE 4

Comparison of Heats of Solution from Roth (56) with Those Calculated from $\frac{du}{dx}$ at 21°C.

SO_2 Concentration gm. SO_2/ 100 gm. H_2O	$\frac{du}{dx}$ at 21° C.	Heats of Solution Calculated* From $\frac{du}{dx}$ cals./mol SO_2	Heats of Solution From Roth at 21° C. cals./mol SO_2	Difference %	$\frac{du}{dx}$ at 100°C.
0.03	0.638	3,730	10,960	65.2	
0.05	0.708	7,460	9,682	29.8	
0.08	0.762	8,790	9,360	15.8	
0.10	0.783	8,950	9,210	11.6	
0.15	0.798	8,920	8,930	2.33	
0.20	0.814	7,550	8,680	2.57	0.796
0.30	0.842	7,200	7,795	7.60	
0.50	0.878	6,700	7,375	10.1	
1.00	0.935	6,470	7,170	10.8	
2.00	0.970	6,360	7,050	7.50	
3.00	0.988	6,300	6,960	7.37	
4.00	0.998	6,450	6,900	7.31	
6.00	0.998	6,450	6,800	5.30	
10.00	0.998	6,450	6,750	4.55	0.575

* Latent heat of water at 21° C. = 10,544 cals./mol.

Discussion of Plotting Methods

A study of Equation (15) at an elevated temperature, say 100° C. will explain why Othmer and White (*49*) concluded their lines were straight and parallel. Values of

du/dx at 100° C. are given in Table 4 for $S = 0.5$ and $S = 10.0$. The ratio of the slopes at 21° C. and 100° C. are, respectively $0.714/0.296 = 2.38$ and $0.608/0.575 = 1.06$. This signifies a greater change of slope with increasing temperature at the low than at the higher concentrations. It also means that straight lines drawn to average the data will have essentially equal average slopes over a wide range of concentration, or in other words, the lines will appear parallel.

The change in slope with increasing temperature on a plot of the latter type is readily explained by the change in degree of the first ionization,

$$H_2SO_3 \rightleftarrows H^+ + HSO_3^-$$

with temperature and concentration changes. As temperature increases the first ionization constant for H_2SO_3 decreases rapidly. This means that the total moles of H_2SO_3 ionizing is less at higher temperatures. Since the heat of ionization (Johnstone and Leppla (*32*) give 3860 cal./mole whereas Roth (*56*) gives 4430 cal./mole at 25° and 21° C. respectively) constitutes a major fraction of the total heat effect, any decrease in ionization will be reflected in significantly lower total heat effects, and thus a lower slope of the vapor-pressure line. This effect is less pronounced at the higher SO_2 concentrations since the moles SO_2 ionized per total mole SO_2 dissolved is less even at normal temperatures. Thus the vapor-pressure lines at high SO_2 concentrations are more nearly straight.

The method of plotting used in this paper, using P_w instead of p_c, tends to offset the effect of diminishing ionization at higher temperatures and concentrations.

Combining Equations (11) and (14) it is shown that the mole fraction of SO_2 in the vapor phase is represented by

$$\frac{P_w - p_w}{P_w} = \left[1 - \frac{p_w^{(a-b)}}{A}\right] \quad (16)$$

As temperature increases at a given SO_2 concentration, p_w increases and $(P_w - p_w)/P_w$ decreases (b is always less than unity and A has a value which will always make $\frac{p_w^{(a-b)}}{A}$ less than unity). Therefore, the mole fraction of H_2O in the vapor phase increases. Since the latent heat of water is greater than the heat of solution of SO_2, the ratio $\Delta H_w/\lambda_w$ will remain more nearly constant as temperature increases.

At higher concentrations where the lines of log $(P_w - p_w)$ versus log p_w are nearly straight anyway, the mole fraction of H_2O in the vapor phase is small and although it increases with temperature, its effect on the total heat of solution is much smaller. Thus, the lines of log P_w versus log p_w are straight in the concentration range $S = 0.03$ to $S = 10.0$, and possess slopes that decrease with increasing concentration.

Nature of SO_2-H_2O System Above 130° C.

It is evident from Figure 1 that extension of the vapor-pressure lines beyond 130° C. will result in a point of intersection of each line with the water reference line. This means, assuming the linear extension valid, that at some temperature the total pressure of aqueous SO_2 solutions and that of pure water is equal. Whitwell and Toner (*70*) observed the same behavior in the case of vapor pressure over textile fibers with adsorbed water. They explained the intersection points by the Eyring (*19*) theory which states simply for this case that the water molecules become more active as temperature increases until they are no longer adsorbed on the surface available and exert a pressure equal to the vapor pressure of water.

No such explanation appears plausible for aqueous solutions of SO_2. Rather it appears more likely that the system undergoes association of some sort which tends to reduce the vapor pressure of SO_2, H_2O or both as temperature increases.

Indeed, it may be shown from the density data of Campbell and Maass (*7*) that aqueous solutions of SO_2 deviate from the ideal solution laws to indicate closer packing of the SO_2 and water molecules. The deviation is more pronounced at elevated temperatures. This raises a question at once as to the validity of linear extension of these curves beyond 130° C. Particularly, it emphasizes the lack of data on the system in this region. Raman spectrum and other composition data on sulfurous acid solutions are available (*1, 6, 20, 28, 53*) but presumably the data were taken at normal temperatures. Until further Raman spectrum analyses are available, the state of the system at temperatures beyond 130° C. will be in the realm of conjecture.

Equilibrium Constants for System SO_2-H_2O

Data on the equilibrium constants for this system have appeared in the literature (*5, 22, 32-33, 37, 56, 61*) in the last half-century. Most of these, however, are based on molal concentrations rather than activities. Sherrill and Noyes (*61*) and Johnstone and Leppla (*32*) alone took into account the interionic attractions of the molecules and calculated activity coefficients from the Debye-Huckel equation. Johnstone and Leppla plotted their calculated results as log K versus $1/T$ and computed a heat of ionization of 3860 cal./mole from the slope. If their data are replotted on an Othmer-Cox chart as log K versus log p_w, two straight lines are obtained (Fig. 2) with a point of intersection at about 21.7° C. The differences in slope correspond to a difference in heat effect of 1070 cal./mole which agrees exceptionally well with the average value of 1060 cal./mole reported by Othmer and Luley (*47*) for seven weak electrolytes which vary widely in nature. Change in state of association of the solvent water according to Dorsey (*17*) was offered as an explanation for this change in slope.

Morgan and Maass (*41*) recognized the effect of molecular association on equilibrium constants for the system SO_2-H_2O and discussed the heptahydrate formation $SO_2 \cdot 7H_2O$, at about 12° C.

Roth (*56*) attempted to determine an equilibrium constant for the reaction

$$SO_2 + H_2O \rightleftarrows H_2SO_3$$

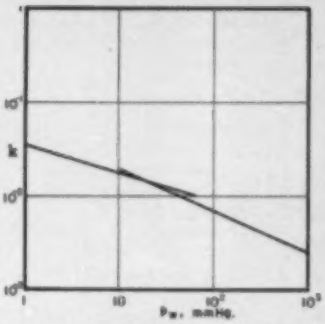

Fig. 2. Modified Othmer-Cox chart showing first ionization constant of sulfurous acid from data of Johnstone and Leppla (*32*)

in the liquid phase. Writing the heat of solution of SO_2 in water as

$$\Delta H_s = \lambda_s + a_h \Delta H_h + a_i \Delta H_i \quad (17)$$

where λ_s = latent heat for pure SO_2; a_h and ΔH_h are the degree and heat of hydrolysis of SO_2, respectively, and a_i and ΔH_i are the degree and heat of the first ionization of sulfurous acid. When a_h is unity, ΔH_s plotted vs. a_i, should give a straight line having a slope of ΔH_i, and an intercept of $\lambda_s + \Delta H_h$. Any deviation from linearity was considered a measure of a_h. By measuring ΔH_s and plotting it against a_i as determined from the conductivity data of Maass, et al (*7, 40*), the value of a_h was calculated from the deviations. Roth then writes:

$$K_h = \frac{[H_2SO_3]}{[SO_2](N)} = \frac{a_h}{(1 - a_h)N} \quad (18)$$

where N = moles H_2O/mole SO_2 and calculates $K_h = 0.064$ at 21° C. He, therefore, considers the degree of hydration, a_h and the concentration of H_2SO_3 at equilibrium to be synonymous. This appears fallacious. In fact, the sum of a_h and a_i exceed the total SO_2 concentration in many cases reported by Roth.

Morgan and Maass (*41*) present a more logical analysis; to obtain K_h, however, they use molal concentrations rather than activities. Their values range from 36.80 at 10° C. to 48.51 at 25° C. which signify an increase in the molecular SO_2 concentration with temperature increase. Their experiments did not extend beyond 25° C. so it may be said only with caution that their trend in K_h is not in agreement with the fact that the vapor-pressure lines on the Othmer-Cox chart cross the water reference line at elevated temperatures.

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Notation

a = statistically determined intercept of the straight vapor-pressure lines on the Othmer-Cox chart

A = antilogarithm of a

b = statistically determined slope of the straight vapor-pressure lines on the Othmer-Cox chart

C,C',C'' = constants of integration

ΔH_h = heat of hydrolysis of SO_2 to H_2SO_3, cal./g. mole

ΔH_i = heat of first ionization of H_2SO_3, cal./g.mole

ΔH_m = heat of solution of a mixture of SO_2 and H_2O vapor in aqueous SO_2 solutions, cal./g.mole

ΔH_s = heat of solution of SO_2 gas in aqueous SO_2 solutions, cal./g.mole

K = equilibrium constant for first ionization of H_2SO_3 based on molal concentrations

K_h = equilibrium constant for hydrolysis of SO_2 to H_2SO_3

k_m,k_s,k_w = ratio $(V_g - V_l)/V_g$ for (a) a mixture of SO_2 and H_2O, (b) for pure SO_2 and (c) for pure water, respectively

n_s,n_w = mole fraction SO_2 and H_2O, respectively, in the vapor phase

N = ratio, moles H_2O/mole SO_2, in the aqueous SO_2 solution

P_m = total pressure above aqueous SO_2 solutions

p_s = vapor pressure of SO_2, over aqueous SO_2 solutions

p_w = vapor pressure of pure H_2O

R = gas law constant

S = SO_2 concentration, g. SO_2/100 g. H_2O

T = abs. temperature, ° K.

ΔV = difference in vapor and liquid volume $V_g - V_l$, upon vaporization of one mole of substance in question

V_g = molal vapor volume

V_l = molal liquid volume

x = $\log_{10} p_w$

y = $\log_{10} P_m$

u = $\log_{10} p_s = \log_{10}(P_m - p_w)$

$Z_m,Z_s,$ Z_w = compressibility factor, pV/RT, for (a) a vapor mixture of SO_2 and H_2O, (b) for pure SO_2 and (c) for pure H_2O

α_i = degree of first ionization of H_2SO_3, moles ionized/mole SO_2

α_h = degree of hydrolysis of SO_2, moles hydrolyzed/mole SO_2

λ_w,λ_s = molal latent heat of vaporization of pure water and pure SO_2, respectively

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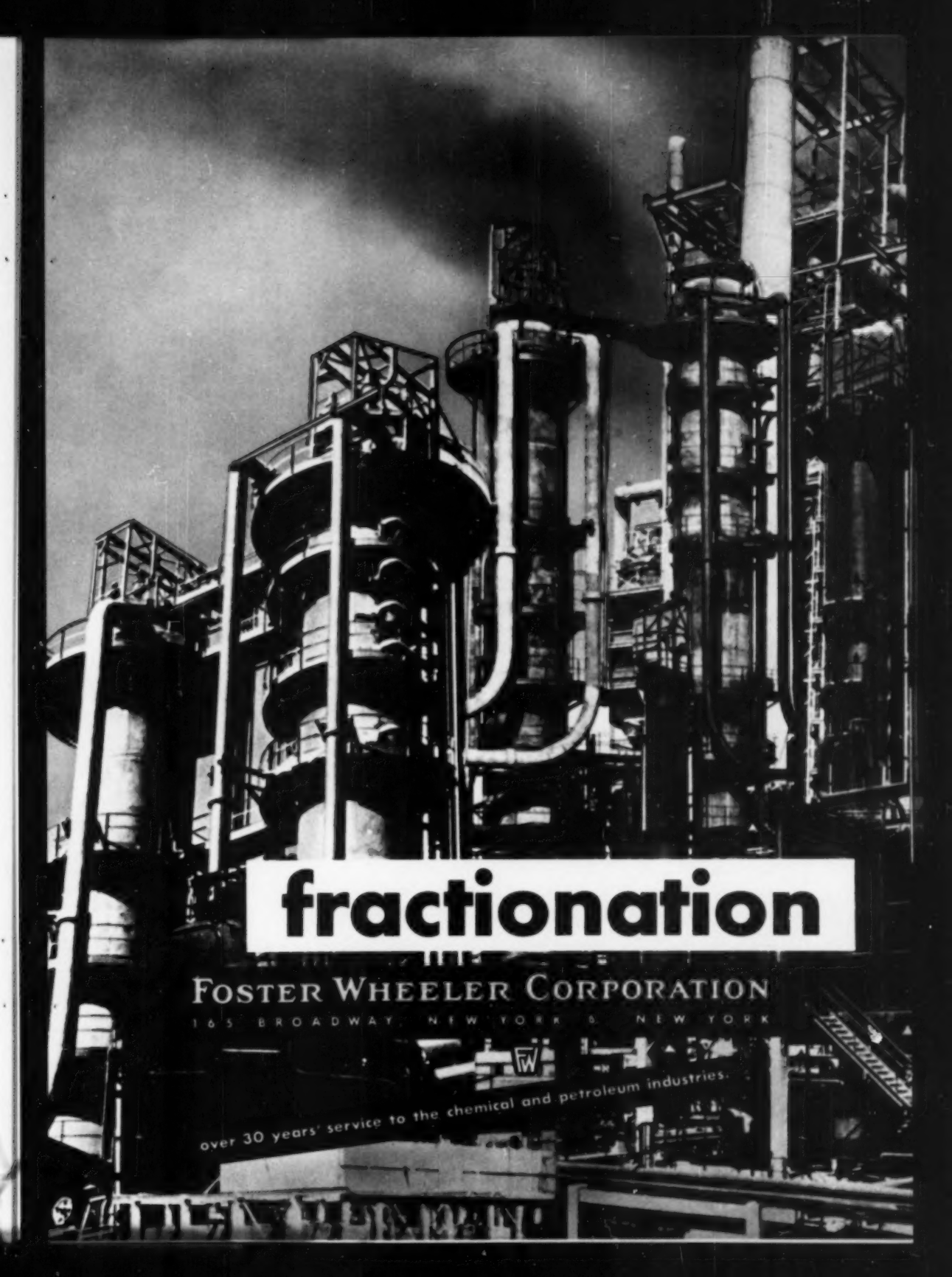
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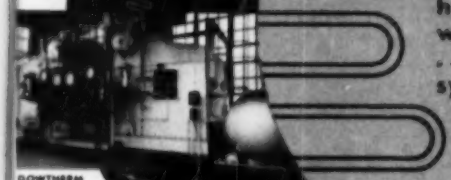

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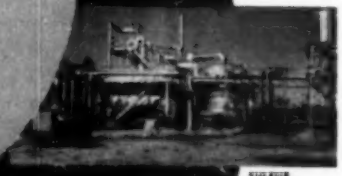

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MINNESOTA IN SEPTEMBER

. . . Site of the A. I. Ch. E.
Minneapolis
Regional Meeting

WILLIAM M. PODAS
Economics Laboratory, Inc., St. Paul, Minnesota

THE Twin City Section will play host to the 15th Regional Meeting of the A.I.Ch.E. Sept. 10-13 at Minneapolis. An outstanding technical program, interesting plant trips, and the scenery and hospitality of Minnesota await you. Headquarters for the meeting will be the Radisson Hotel in downtown Minneapolis.

Robert J. Foster (General Mills, Inc.) is General Chairman of the Minneapolis meeting. Edgar L. Piret (University of Minnesota) is Chairman of the technical program which will consist of six symposia and a general-papers session. The program will have a wide appeal to management, teaching, production, research, and construction groups. The symposia and chairmen are as follows:

1. What Should You Know About Management? (Loren P. Scoville)
2. Phase Equilibria (Wayne C. Edmister)
3. Applied Reaction Kinetics (Richard H. Wilhelm)
4. Quantitative Economics in Estimation of Risk Factors in Capital Ventures (Mott Souders, Jr.)
5. Indoor Versus Outdoor Plant Construction (Joseph R. Minevitch)
6. Chemical Engineering in the Food Industries (William L. Faith)
7. General Technical Program (Edgar L. Piret)

The Twin City Section of the Institute is only one year old but chemical engineering as a profession has been long established in Minnesota. The University of Minnesota has had an A.I.Ch.E. accredited chemical engineering curriculum since 1925 and has sent its graduates into industrial, research, and teaching positions all over the country. A special invitation to the Minneapolis meeting is extended to Minnesota men to come and visit old friends and familiar scenes and see the new chemical engineering building. Some applications of chemical engineering in Minnesota as represented by flour milling and linseed oil are partially based on geography and agricultural economics. Other applications of chemical engineering as represented by Minnesota Mining and Manufacturing Co. (sandpaper, Scotch tape, fluorocarbons, etc.) are based not so much on geography as on pure and applied research. The Twin City section has a membership of 95 and a mailing list of 220 chemical engineers throughout the state. Some of the products or activities represented by its members are: teaching, consulting, flour milling, glass, linseed oil, public utilities, wood products, detergents, food canning, lithium products, paint, cosmetics, paper, recording tape, abrasives.

Courtesy Minneapolis Chamber of Commerce
Minnehaha Falls.

This city and her "twin" St. Paul, have a metropolitan population of more than one million. The two cities are at the head of navigation on the Mississippi River. The source of the Mississippi River is in Itasca State Park in the heart of Northern Minnesota's vacation country. Minneapolis lies 15 miles up the winding river from St. Paul; their city halls are 10 miles apart and their city borders overlap. They form one metropolitan trade and manufacturing center serving all Minnesota plus parts of Iowa, Wisconsin, Michigan, North and South Dakota, and Montana.

The Twin Cities are the center of one of the greatest agricultural areas in the world. Among the 48 states Minnesota ranks first in butter and flax, second in oats and eggs, third in rye and milk, fourth in corn and hay. For 70 years Minneapolis has been known as the flour-milling center of the world. A flour mill was one of the first structures to be erected at St. Anthony Falls on the Mississippi River. Minneapolis is the headquarters for the five largest flour-milling companies in the United States. Minnesota and the Dakotas raise about 80% of the country's flax, most of the flax seed comes to Minneapolis for processing into linseed oil and the by-product oil cake. The ready supply of linseed and soybean oils has given rise to a large paint industry. The dairy

Courtesy Minneapolis Chamber of Commerce

Aerial View, Minneapolis Business District.

farm is the most important kind of farm and Minnesota and its Wisconsin neighbor comprise the No. 1 "milk-shed" of the United States. South St. Paul is a great meat-packing center, currently ranking second in the country in total receipt and sale of all livestock.

The mineral wealth of Minnesota is synonomous with iron ore. The iron mines of Minnesota supply about 65% of the country's total production. The open pit mine at Hibbing is the largest in the world, 2½ miles long and ½ mile wide with 60 miles of railroad track. The tremendous industrial demand for steel has imposed a heavy drain on the iron-ore resources of Minnesota, but conservation and research are live issues on the iron ranges. Most of Minnesota's ore is shipped from the port of Duluth which ranks second only to New York in harbor tonnage handled.

The Twin Cities have a large and diverse manufacturing output: agricultural machinery, metal products, automobiles, storage batteries, textiles, heating and regulating equipment, refrigerators, advertising specialties, hearing aids, hoist equipment, food products.

Geography itself is one of the Twin Cities' main attractions. Several large lakes lie within the city limits and there are acres of parks and miles of driving on tree-lined parkways. Golf courses, tennis courts, and swimming beaches are spread in and around the cities. Indian names are common, Minnesota itself means "land of sky-blue water." Minnehaha Falls in Minneapolis is referred to in Longfellow's poem, "Hiawatha." 15 miles west of Minneapolis is the beautiful lake which inspired the song "By the Waters of Minnetonka."

From a cultural standpoint the Twin Cities have much to offer. The University of Minnesota is the second largest state university in the country. The main campus is in Minneapolis 1 mile from the Radisson Hotel and the agricultural campus is in St. Paul 3 miles away. The University's new Chemical Engineering Building will be officially opened this year. Minneapolis has an excellent symphony orchestra, the Minneapolis Institute of Art, the Walker Art Center, and the University of Minnesota Gallery. St. Paul has the State Capitol, the James J. Hill Reference Library, the Minnesota Historical Society Buildings and the Como Park botanical conservatory.

September is usually the nicest month of the year in Minnesota and you may want to plan a little vacation trip to points of interest throughout the state such as the Mesabi Iron Range (225 miles north of Minneapolis), Duluth and its ore docks (170 miles northeast), the Mayo Medical Center at Rochester (75 miles southeast). Attractions like Superior National Forest with its Gunflint Trail and the North Shore Drive along Lake Superior draw thousands of visitors to Minnesota each year. For a real vacation, a fishing trip to one of Minnesota's 10,000 lakes is highly recommended. Information will be available at meeting headquarters.

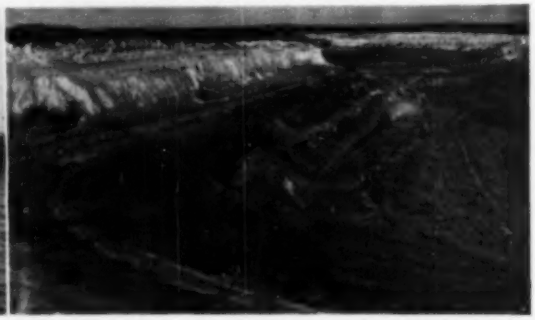
The Twin Cities are a transportation hub and can be easily reached by train, airplane, bus or auto. The Twin Cities are 6½ hr. by train (three different railroads) or 1¾ hr. by airplane from Chicago. Northwest Airlines has a 3½-hr. nonstop service from New York to the Twin Cities. The Rock Island Railroad and Mid Continent Airlines both serve the Twin Cities from the south (Kansas City, Houston, etc.). Three transcontinental railroads run from the Twin Cities to the Pacific coast.

The Minneapolis meeting will include an excellent ladies program and wives are cordially invited. The Radisson Hotel is just off Nicollet Avenue, one of the finest shopping districts in the country. Trips will be arranged to near-by parks, historical spots, and other points of interest.

The Twin City Section cordially invites you to the Minneapolis Regional Meeting, Sept. 10-13.

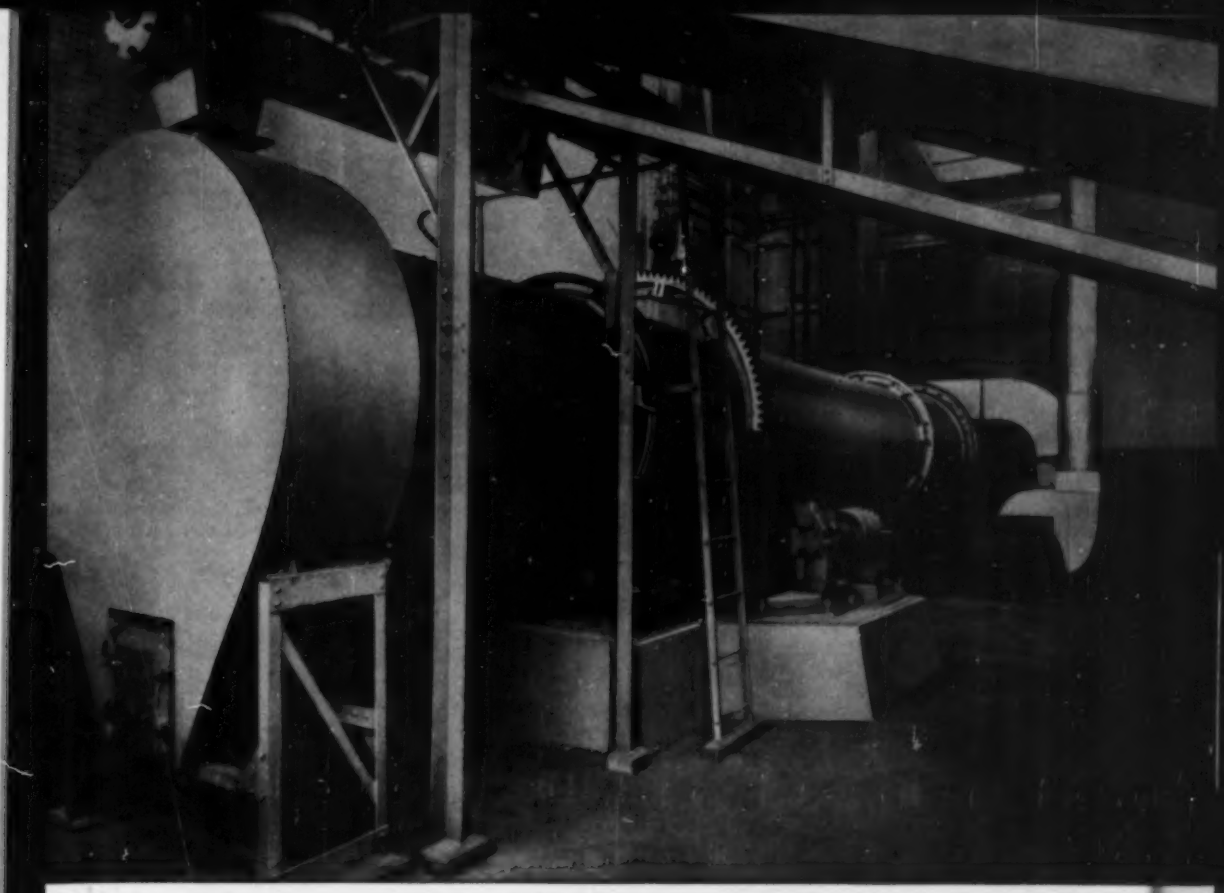
Courtesy Division of Publicity, Minnesota Dept. of Business Res. and Dev.

A 16-lb. Northern Pike Caught at Blackduck Lake.



Courtesy Division of Publicity, Minnesota Dept. of Business Res. and Dev.

Mahoning-Hull-Rust Open Pit Iron Mine at Hibbing.



"Technical Approach"

can help solve your drying problems too

YEARS AGO it was an adventure, this matter of dryer design. Recommendations were made almost blindly, based largely on experience with other —and frequently dissimilar materials. Guess-work bulked large in the decisions. But the Bartlett-Snow heat engineers have changed all this.

"Technical Approach",—the advantage of mathematical formulas developed, tested and proved by our heat processing engineers has replaced guess-work — and luck — in Bartlett-Snow design. All factors — including those of surface evaporation and diffusion, corrosion, abrasion, the tendency to cake in cooling, the dust condition, and possible galvanic action are disassembled from each other, studied, and checked.

Findings are verified when necessary, by running samples of the material through an ingeniously arranged rotary test dryer. Thus all requirements of the problem become known, —and full allowance for all conditions can be made in designing the equipment to be built.

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Send for Bulletin No. 89. It describes the nature and scope of our services in detail—and let the Bartlett-Snow heat engineers work with you on your next heat engineering problem. The C. O. Bartlett & Snow Co., Cleveland 5, Ohio. Engineering representatives in New York, Baltimore, Detroit and Chicago.

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MORE ON SWAMPSCOTT, OR _____

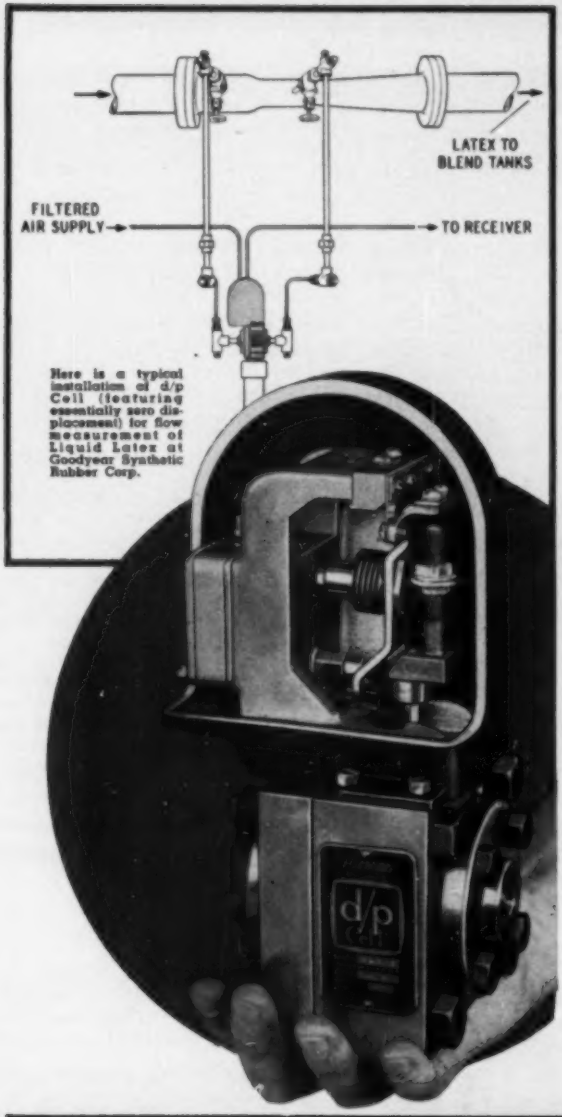
FURTHER piscatorial palaver from the habitat of the Kingfish, Mackerel, Smelt and Shark, collectively known as Ichythologists—Illustrated below are just a few of the various "goings-on" which took place at the Swampscott Regional Meeting. At the top left, the square dance which might not have been held but for the stubborness of Bill Rousseau, entertainment chairman. Bill's position was fully vindicated by an exhausted but thoroughly entertained group of chemical engineers, and their ladies who turned out in full and who had to be told when it was time to go home. In the upper right is

Original Ichthyologists, A. L. Gardner, Monsanto Chemical Co.; Gustavus J. Esselen, U. S. Testings Co.; H. J. Skinner, Skinner & Sherman, Inc., and P. J. Curtis, Monsanto Chemical Co.

Neil Sargent, the Finance Chairman, counting his money. This pose was continuous throughout the meeting but his diligence was rewarded in the end with every penny accounted for. Council is shown in full weighty deliberation of Institute affairs on the left. On the left and lower right are shown two of the industrial exhibits set up in the lobby of the hotel headquarters, the Brush Development Corp's. exhibit of a laboratory scale ultrasonic generator on the left with two members of that organization who demonstrated the unit. On the right J. E. Vivian, M.I.T., and Henry

(*Continued on page* 19)

NOW – measure flow of viscous or corrosive fluids without seal pots



Here is a typical installation of d/p Cell (featuring essentially zero displacement) for flow measurement of Liquid Latex at Goodyear Synthetic Rubber Corp.

You can cross seal pot troubles right off your list when you measure the flow of viscous or corrosive liquids with a Foxboro d/p Cell (differential pressure pneumatic transmitter). Goodyear did it very successfully on one of the toughest jobs . . . the control of latex flow to a coagulator. Here are the results obtained by this leading manufacturer through the use of the mercuryless d/p Cell:

A. 83% reduction of instrument cleaning and maintenance costs.

B. No unscheduled production shut-downs for instrument maintenance.

C. Estimated savings over previous flow measuring system will return cost of d/p Cell installation in approximately 1 year.

These cost-saving achievements were made possible by the elimination of seal pot disadvantages . . . (frequent and time-consuming clean-outs, constant risk of clogging, instrument inaccuracies, etc.). A complete "Technical Report on Savings Effected at Goodyear Synthetic Rubber Corporation through Control of Latex Flow by d/p Cell" is available. Send for a copy and details of the unique d/p Cell. The Foxboro Company, 16 Neponset Ave., Foxboro, Mass., U. S. A.

FOXBORO REG. U. S. PAT. OFF.

d/p CELL for better flow measurement

Problem: How to Handle with Safety Highly Viscous Materials Under Pressure

Chemical engineers of many of the nation's largest industrial plants have watched with interest development of the NEW BS&B T-ASSEMBLY SAFETY HEAD. It is already in demand. It is recommended for chemical plants handling viscous materials.

No other relief device acts as quickly as the BS&B SAFETY HEAD. It consists of three principal parts . . . a pre-formed metal rupture disc and two specially designed holding flanges. Correct element resistant metals are used in fabrication of the rupture disc, which bursts when a predetermined pressure is reached. Instantly a fully unrestricted escape for gases and liquids takes place. And, as quickly the possible dangers of property damage, fires and injuries to personnel vanish.

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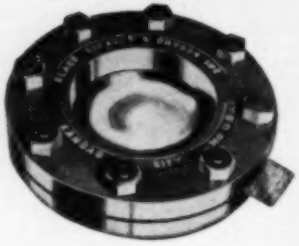
The BS&B SAFETY HEAD story is fully covered in a new catalog. Send for your free copy NOW! Use coupon on the opposite page. Once you understand your need for SAFETY HEADS, you won't delay.

Free Analysis Without Obligation

Jim Myers, SAFETY HEAD Sales Manager will have a BS&B engineer analyze your pressure relief problems and submit suggestions to you WITHOUT COST OR OBLIGATION. Mail coupon on opposite page or call GRand 0700, Kansas City, Mo. DO IT NOW!

Do You need T-ASSEMBLY SAFETY HEADS?

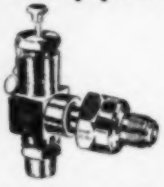


The answer is YES . . . to every chemical plant using viscous materials under pressure provided the liquid contacts the metal rupture disc. Such plants should not be without this new positive protection relief device. Read the details on "How a T-ASSEMBLY SAFETY HEAD Works" on the opposite page. This newly designed T-Assemly unit is the combined art of the highest achievement of metallurgical and engineering skill.

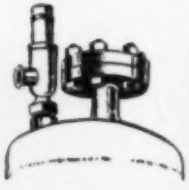
Here Are Your Answers to Relief Valve Problems--Extra Protection for Expensive Equipment

This installation is used when it is not necessary to have a shut-off or when materials handled are not toxic or inflammable.

A SAFETY HEAD at the relief outlet will stop leakage until rupture disc pressure is attained. Not recommended where viscous or corrosive materials might contaminate internal parts of the valve. Investigate your valve design before using this type of installation.

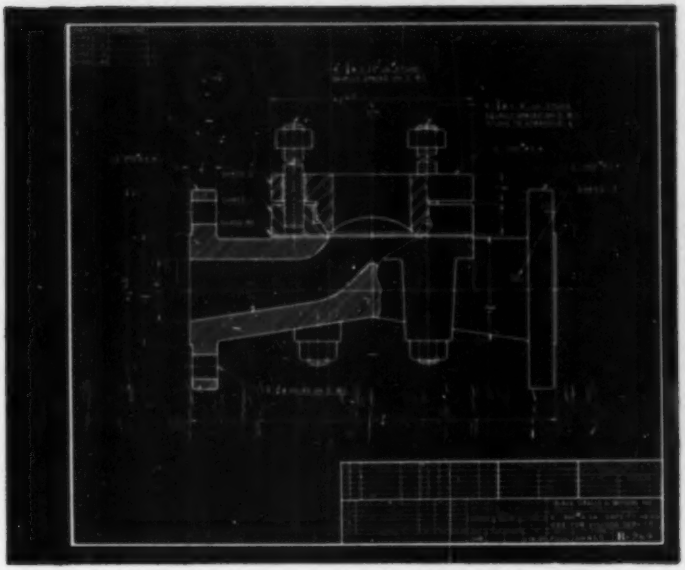


A SAFETY HEAD under your relief valve isolates the valve from the vessel contents. This stops leakage through relief valve until SAFETY HEAD disc is burst by overpressure. An open bleed line or some type of telltale indicator must be installed in chamber between rupture disc and valve plug.



When the SAFETY HEAD is used as secondary relief device you are given positive protection when pressure rises to the predetermined bursting pressure of the rupture disc. The primary relief valve may fail to function due to corrosion, or pressure continues to rise due to inadequate relief area

Solution: .... BS&B T-ASSEMBLY SAFETY HEADS



How the T-ASSEMBLY SAFETY HEAD Works

The shaded portions of the above diagram indicate a curved channel designed by BS&B through which the viscous material washes against the rupture disc. This material moves on through the passage if no undue pressure rise occurs. However, if the passage becomes blocked, such material will tend to solidify quickly, causing a dangerous pressure rise. In that case, the SAFETY HEAD rupture disc bursts and the pressure is given a fully unrestricted opening.

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☐ Please have a BS&B SAFETY HEAD engineer analyze my relief problem, without cost or obligation to me.

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BS&B SAFETY HEADS

SWAMPSCOTT STORY

(Continued from page 16)

Avery, Godfrey L. Cabot, Inc., look over the Cabot exhibit of vinyl resin plasticizers. At the right center is a view from the hotel with Swampscott Bay glimpsed dimly through the haze in the background. One of the plant trip busses is about to start while a skeptical chemical engineer prognosticates the weather with accurate instruments in the foreground. At the lower left "Able Andy" Stokes & "Wild Jim" Donovan, Godfrey L. Cabot, Inc., and Artisan Metal Products respectively, prepare to ride forth in best Paul Revere tradition. They are being closely observed by a female named Betsy whose last name and company affiliation were not recorded.

Bertel Greffrath and family, their car and trailer in which they drove from their home in Richland, Wash., as they arrived at the Swampscott meeting.

Ultrasonics

On the more serious side two features of the Swampscott meeting not already reported on in the June issue of C.E.P. were the Ultrasonics Symposium organized by Dudley Thompson, V.P.I. and the Fluidized Solids symposium under E. R. Gilliland, M.I.T. The Ultrasonics Symposium was initiated at the Houston Regional Meeting with two papers and continued at Swampscott with six additional papers in the first symposium on the subject to be held before chemical engineers. To date, ultrasonics has definitely proved itself a practical tool in the agglomeration of fine particles in dust- and mist-collection systems. This was brought out in a paper by C. A. Stokes, Godfrey L. Cabot, Inc., and J. E. Vivian, M.I.T., entitled, "Sonic Energy in the Process Industries." Installations have been made for the collection of sulfuric acid mists and carbon black by subjecting the droplets or particles to a high intensity sound field which causes agglomeration of the mist

or dust into larger particles which can be removed with conventional cyclone separators. Some application, the authors stated, has been made to the dispersion of solids in liquids or liquids in liquids. However, thus far, progress has been generally hindered by the lack of methods for applying with reasonable efficiency sonic energy to process materials.

Alfred Weissler, Naval Research Laboratory, discussed the "Physico-Chemical Effects of Ultrasonics" and presented a motion picture, in color, illustrating the effect of high frequency energy, approximately 500,000 cycles/sec., applied to an aqueous solution of potassium iodide and carbon tetrachloride. Iodine was liberated when the ultrasonic energy disrupted the carbon tetrachloride molecule liberating chlorine which in turn displaced free iodine from the potassium iodide solution.

Robert Spencer, Dow Chemical Co., winner of the A.I.Ch.E. award for the best-presented paper at Swampscott.

Karl Sollner, National Institute of Health, in "Colloidal Effects of Ultrasonics" reviewed his own work and that of other investigators on the application of ultrasonic energy in the creation and destruction of colloidal systems. He also discussed the effect of ultrasonic energy on existing colloidal systems. Several applications were described by Dr. Sollner which may come to have practical significance. Extremely fine-grained and highly sensitive photographic emulsions have been prepared, he said, by irradiating silver bromide emulsions with ultrasonic energy. Improvements in dyeing processes, the rupture of oxide films necessary in metal plating processes, emulsion breaking, emulsification, dispersion of metals within metals in the molten state where solution does not take place, are a few applications mentioned in which preliminary work has been done. Dr. Sollner also spoke on various types of ultrasonic generators, listing the advantages and disadvantages of each and the practical power levels of operation. He stressed a need for better understanding of the complex mechanisms involved in ultrasonic systems and said that wider application of this tool will be achieved only through such understanding.

J. J. Healy, Jr., Monsanto Chemical Co., and Chairman of the Committee on Arrangements at Swampscott.

"Material Testing and Gaging with Ultrasonics" was the title of the paper given by Benson Carlin, Smith Meeker Engineering Co. He described three techniques finding general application currently: (1) passage of continuous ultrasonic waves through material, (2) transmission and reflection of short pulses within material, and (3) resonance effects. These techniques are finding wide application in the detection of flaws in structural materials and in the measurement of lamination or stratification thicknesses within solid bodies. This method of testing metals for flaws offers many advantages over X-ray and magna-flux inspections in its ready adaptation to testing structures of all shapes and sizes with relatively simple equipment.

The Ultrasonics Symposium concluded with a round-table discussion panel composed of the various speakers and several other experts in the field of ultrasonics. The general response from chemical engineers attending the symposium was that they were eager to be kept informed of new developments.

The concluding technical session of the meeting was the Fluidized Solids Symposium presided over by E. R. Gilliland, of M.I.T., with six papers being presented. R. D. Morse and C. O. Ballou, Du Pont Co., described an electrical probe for measuring the density of fluidized beds and for locating the size of gas bubbles and the degree of slugging in fluidized systems. M. P. Sweeny, E. R. Gilliland and W. K. Lewis reviewed their work on a fluid system for producing pure carbon dioxide by means of the reaction between ferric oxide with coke at a temperature of 800° to 1050° C.

Best-Presented Paper

Robert Spencer, Dow Chemical Co., received the award for the best presentation of any paper at the Swampscott Meeting. He and Noland Poffenberger, also of Dow, were coauthors of the paper, "Equilibrium State of Catalysts in Moving Bed Reactor Systems," one of the papers in the Fluid Solids Symposium.

Furthest traveled of anyone attending the Swampscott Meeting was Bertel Greffrath, of the Columbia Valley Section of A.I.Ch.E. in Richland, Wash. Mr. Greffrath drove with his wife and three children towing a trailer behind his car. His arrival at Swampscott was welcomed with full Ichthyologist hospitality.

Left: Speakers at the Fluidized Solids Symposium, R. D. Morse, Du Pont Co.; M. P. Sweeney, M.I.T.; E. R. Gilliland, M.I.T.; D. E. Boynton, M.I.T., and G. P. Hinds, Shell Oil Co.

Right: Panel on Ultrasonics, R. H. Bolt, M.I.T.; A. Weisler, Naval Research Labs.; Dudley Thompson, Virginia Polytechnic Institute; Karl Sollner, National Institute of Health; J. B. Roberts, Du Pont Co.; Benson Carlin, Smith Meeker Eng. Co.; J. W. Butterworth, Brush Devel. Co., and F. J. Van Antwerpen, Chemical Engineering Progress.

there's no "CURE-ALL" for industrial waste treatment...

No two waste treatment problems are exactly alike . . . and no single equipment unit can be the solution to them all. Diversified equipment and diversified experience are essential to a successful and economical solution . . . and Dorr has both.

The first Dorr-equipped waste treatment plant was installed at a New England textile mill in 1915. Since then, Dorr equipment and methods have been employed for the treatment of both organic and inorganic wastes of virtually every kind.

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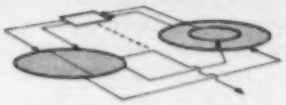
Three typical Dorr-equipped waste treatment plants . . .

A West Coast sewage plant had its load doubled by scum-forming cannery wastes five months out of twelve, virtually putting it out of commission. A Dorrco Vacuator, Biofiltration with a Dorrco Distributor and a final Dorr Clarifier have completely eliminated the scum problem and put the plant on a year-round basis.

60 gal/min with a BOD of 700 ppm, are being treated effectively with a Dorr single-stage Biofiltration System. Equipment includes a Dorr Primary Clarifier, Dorrco Distributor, plain final clarifier, and a Dorr Digester equipped with high capacity mixing.



Packing house wastes from a residentially located meat products plant are given complete treatment in an area less than 80' x 100'. A Dorr Duo-Clarigester combined with a Dorrco Duo-Filter provide two-stages of Biofiltration followed by digestion.

If you have a waste treatment problem we would welcome the opportunity to work with your consulting engineers. If you are a consulting engineer actively engaged in waste treatment, our experience is at your disposal.

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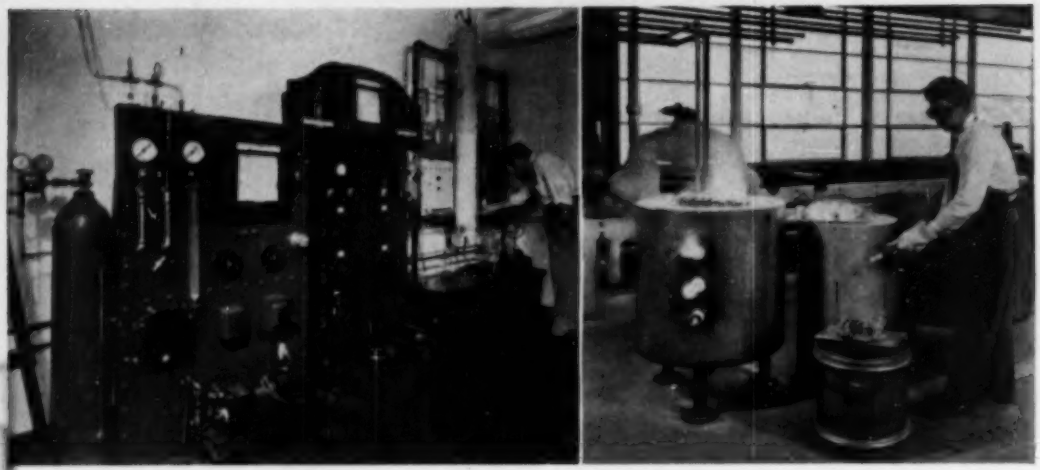
ALCO'S NEW RESEARCH LABORATORY IN EAST ST. LOUIS



Interior view of part of the new research area of the Aluminum Company of America at East St. Louis, Ill., show the experimental furnace where aluminum oxide is converted to tabular alumina by heating to a temperature near the fusion point. In the picture white hot tabular alumina balls are being dropped into a beaker of cold water. Shown on left is a laboratory used for investigating catalytic applications for alumina.

The new laboratory is a three-story structure; at its rear is the development laboratory. The pilot plant can accommodate materials in carload lots. Among the pieces of equipment available for use are a 60-ft. rotary kiln with variable speed and adjustable pitch; a 500-kw. three-phase electric furnace and a variety of driers, filters and sintering machines.

The purpose in constructing this new building is to house adequately the laboratory phase of the company's investigations. The work is concerned primarily with the products of Aluminum Ore Co., the various forms of aluminum oxide (alumina) and fluorides. The East St. Louis branch of Aluminum Research Laboratories is one of Alcoa's four research centers. The East St. Louis research program, however, concerns the production of alumina from bauxite as well as the development and improvement of related ore products.

EDUCATION COMM. CONSIDERS BASIC PROBLEMS —ELECTS OFFICERS

The Citizens Federal Committee on Education, a lay advisory committee to the U. S. Commissioner of Education, recently elected as its chairman, Ralph L. Goetzenberger, of the Engineers' Council for Professional Development, New York, to succeed Dr. Kathryn McHale, general director, American Association of University Women.

John T. Corbett was elected vice-chairman; Margaret Hickey of the National Federation of Business and Professional Women, St. Louis, was elected secretary at the eighth semi-annual meeting held in Washington, D. C., May 18 and 19.

The two new members of the Executive Committee are Mrs. Edmonia Davidson and Rev. Frank Tishkins.

Made up of 33 members representing agriculture, business, homemakers, labor, etc., the Citizens Federal Committee on Education meets every six months for an exchange of free discussion of the problems of improving educational standards.

Under the direction of Earl James McGrath, U. S. Commissioner of Education, the members of the Citizens Federal Committee gave consideration to basic problems and broad programs of education.

A.B.C.C. REPORTS AVAILABLE FOR DEFENSE HERE

Formation of eye cataracts, the first evidence of delayed effects of the atomic bombings at Hiroshima and Nagasaki, has been entered into the records of the Atomic Bomb Casualty Commission of the National Research Council. Since the Japanese survivors make up the only group of people who have been exposed to an atomic bomb burst the medical findings of the A.B.C.C. have significance for scientists and for military and civil defense planning in the United States. These findings will be made available to the U. S. Public Health Service and other agencies.

Scattered studies of the effects of the bomb blast were begun by medical observers attached to the Allied occupying forces in 1945. To organize the work on a more orderly basis, the A.B.C.C. was set up by the National Research Council under the committee on Atomic Casualties. Following the discovery that radiation similar to that released in an atomic bomb burst had caused cataracts to form in the eyes of research workers in this country a preliminary ophthalmic survey was started at Hiroshima last year. This survey revealed ten cases of cataracts believed to have been caused by the atomic bomb. Subsequent examination led to the discovery of about 40 certain cases of radiation cataract and an additional 40 suspected cases. A full-scale ophthalmological study is now under way at Hiroshima and a survey of survivors at Nagasaki is also planned.

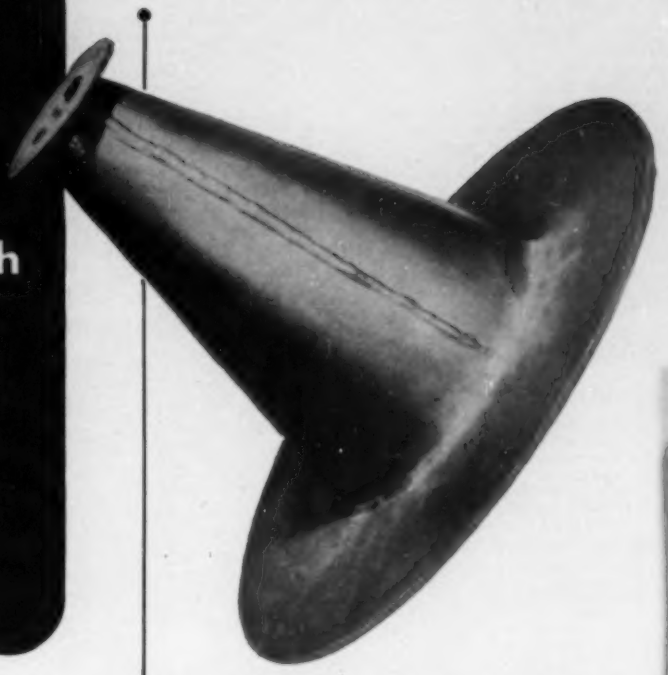
These facts are contained in a recent release of the Atomic Energy Commission. Many unexpected problems have been met and solved in full or in part during the 3-year period over which the A.B.C.C. has been operating.

The first studies of atomic bomb casualties were carried out in late 1945 and early 1946 by the Joint Commission for the Investigation of the atomic bombing in Japan.

A second survey group worked in Japan during the latter part of 1946 and the early part of 1947. When this group departed from Japan there remained behind a nucleus consisting of one naval and two army medical officers to carry out an interim program. The Atomic Bomb Casualty Commission has grown from this nucleus.

(More News on page 24)

8 TIMES longer life in wet chlorine with HASTELLOY alloy C reducers



Used to introduce chlorine gas into a chlorinator at 100 deg. F., these HASTELLOY alloy reducers are still in operation after one year's service. The material previously used, iron-silicon alloy castings, failed because of poor mechanical strength.

The cost of each HASTELLOY alloy reducer has been about seventy cents a day, based on actual performance records to date, and since the reducers are still in service the final cost figure will be even lower.

The reducers were fabricated from HASTELLOY alloy C sheet. Ten-gage sheet was cut to size, rolled in the shape of a cone, and then welded to form the body. The top and bottom flanges were circle-cut from 12-gage sheet and then welded to the body. The assembly was then solution-treated to impart maximum corrosion resistance. All welds were made with a HELIARC torch using alloy C bare drawn wire.

The story of these reducers proves once again that HASTELLOY alloys resist severe corrosion . . . are easy to fabricate . . . and are economical to use. They could be the solution to your corrosion problem. Fill out the coupon below for the new 40-page booklet giving the full story of the four grades of HASTELLOY alloys. The booklet will help you select the grade you think most suited to handle your problem.

"Hastelloy", "Haynes" and "Heliarc" are trade-marks of Union Carbide and Carbon Corporation or its Units.

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Please send me without obligation a copy of the 40-page booklet "HASTELLOY Nickel-Base Alloys"

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Company_____

Address_____

THIRD WORLD PETROLEUM CONGRESS AT HAGUE

The Third World Petroleum Congress will be held at the Hague, Holland, May 28-June 6, 1951. C. G. Kirkbride, vice-president of the Houdry Process Corp., and a director of American Institute of Chemical Engineers, is chairman of the U. S. National Committee for the Congress and members of the A.I.Ch.E. who desire to submit papers should direct them to his attention at the Houdry Process Corp., Marcus Hook, Pa. Titles of papers to be submitted are desired as soon as possible, as a provisional list of all papers expected will be published.

The Congress will cover many subjects of interest to chemical engineers. These include the following:

Physical Operations in Oil Processing.

1. Phase equilibria
2. Distillation
3. Extraction
4. Adsorption
5. Crystallization
6. Heat and mass transfer

Oil Processes Involving Chemical Conversions.

1. Hydrogenation and hydrocarbon synthesis
2. Cracking and reforming (catalytic and thermal)
3. Polymerization, alkylation, isomerization
4. Chemical treating processes

Production of Chemicals from Petroleum; Their Properties and Applications.

1. Solvents
2. Miscellaneous chemical intermediates
3. High molecular compounds
4. Detergents
5. Biocides
6. Fertilizers

Construction of Equipment. Materials, Corrosion

1. Equipment for refineries
2. Equipment for chemical factories
3. High pressure equipment
4. Safety equipment
5. Standardization

Other subjects to be covered at the Congress are:

Geology, Geophysics; Drilling and Production; Measurement and Control-Analysis and Testing; Utilization of Oil Products; Transport, Storage and Distribution, and Economics and Statistics, Documentation.

LITHIUM PRICE DOWN

Price reductions up to 10 per cent were announced this month by Foote Mineral Co., producers of lithium compounds used extensively in all-purpose greases, ceramics and porcelain enamels, air conditioning, welding fluxes and many chemical products.

L. G. Bliss, manager of sales, said that savings from newly developed processing techniques make possible this action. He also revealed that in the past decade the cost of many lithium compounds has been halved.

CHEM. ECONOMICS HANDBOOK—STANFORD

A chemical economics handbook for service to business and industry and available on a subscription basis of $250 a year, is a new project of the Stanford Research Institute. The economic study is under the direction of Raymond H. Ewell. Additional concurrent subscriptions will cost $60.

The new handbook will be in loose-leaf form, punched to fit standard 8½ x 11-in. ring binders. The present plan is to issue 250 separate data sheets on various phases of the chemical field in the following large areas:

Economic Indicators, Major Industries and Commodities, Chemical and Allied Process Industries, Raw Materials, End Chemical Groups, Organic Chemicals, Inorganic Chemicals. The first data sheets will be ready July 15.

Data for the handbook will come from the government, trade associations, and miscellaneous other sources.

During 1950 the Research Institute expects to have data sheets on production of all chemicals produced to the extent of more than $5,000,000 a year, and will cover many chemicals in the range of $1,000,000 to $5,000,000 a year.

Only a few sheets, according to the present plans, will be issued this year on items having a production value of less than $1,000,000. During subsequent years, however, data sheets will be issued on the smaller value chemicals as well as continuing additional information on major chemical production.

(*Continued on page 36*)

LETTER TO THE EDITOR

WATER PIPE CLOGGED BY CLUSTER OF MUSHROOMS

Sir:

An unusual problem in the use of cooling towers for process water was encountered last summer at the Brooklyn plant of Chas. Pfizer & Co., Inc. It was first observed that the water flow to one of the vacuum pan condensers was decreasing rapidly, and it was thought that some foreign matter had become lodged in the pipe. When flow had been reduced to an inoperable level, the pipe line was dismantled, and in one of the reducing bushings a clump of mushrooms was found growing (*see illustration*).

No additive was used in this system to prevent algae or bacterial growth. If this precaution had been observed, it is doubtful whether the fungus growth would have been encountered. Under the existing conditions, apparently enough organic matter was picked up by the water recirculating through the forced draft tower to provide sufficient food for the fungus to grow.

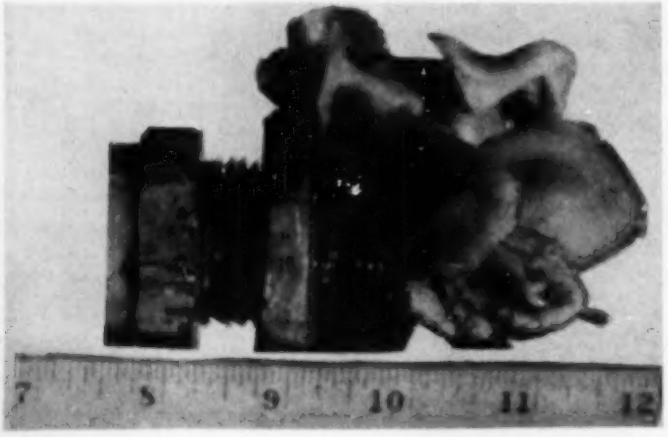
The fungus was tentatively identified as *Clitocybe multiceps* Pk.

J. B. Routien
A. J. Greene
Brooklyn, N. Y.

March 27, 1950

(*More News on page 28*)

FUNGUS GROWTH STOPS COOLING WATER FLOW



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PERFORMANCE

Here is the famous Lapp solid-porcelain valve which has served spectacularly for many years in so many applications involving handling of corrosive chemicals—now reinforced for production security with a completely-enclosing shell of high-strength aluminum. Compare the table of prices for this equipment with that of lined valves, alloy valves, or any valves which will handle your difficult corrosion problems. On a straight dollar-and-cents basis, the Lapp *Armored* valve of *solid porcelain* is your best bargain in corrosion-resistant valves.

PRICE

LAPP ARMORED PORCELAIN "Y" VALVES

1"	$68	3"	$105
1½"	74	4"	137
2"	79	6"	263

LAPP ARMORED PORCELAIN ANGLE VALVES

1"	$68	2"	$79

LAPP ARMORED PORCELAIN FLUSH VALVES

1½" (for 3" tank outlet)	$168
2" (for 4" tank outlet)	205
3" (for 5" tank outlet)	242

WRITE *for complete information and specifications. Lapp Insulator Company, Inc. Process Equipment Division, 254 Maple St., LeRoy, N. Y.*

Lapp

PROCESS EQUIPMENT

CHEMICAL PORCELAIN VALVES • PIPE • RASCHIG RINGS

PULSAFEEDER CHEMICAL PROPORTIONING PUMPS

MARGINAL NOTES

News of Books of Interest to Chemical Engineers

25 Years of Nonograms

An Index of Nomograms. Douglas Payne Adams. John Wiley & Sons, Inc., New York, N. Y. (1950) 174 pp. $4.00.

Reviewed by F. J. Van Antwerpen, Editor, Chemical Engineering Progress.

THIS is an index of nomograms published in the technical literature from 1923 to date. There are no nomograms in the book, merely details as to type of nomogram, and the periodical, year, month, volume, and page number where it can be found.

The author has divided it into the following subjects: Mathematics, Physics, Chemical Engineering and Chemistry, Electricity, Hydraulics and Power, Water Works, Oil and Gas, Illumination, Aeronautics, Heating and Piping, etc., Building, Structures, Highways, Machine Design, Machine Tools, Welding, Metals, Mining, Paper, Textiles, Medicine and Food.

The work is not complete, as the author admits, since only those periodicals were searched which patently favored the publication of this type of diagram. However, in view of the publications that were covered, one is led to believe that few important nomograms could have been missed.

For the engineering staffs using nomograms consistently for new problems, this will be an important addition to their literature on the subject.

Smog and Visibility

The Smog Problem in Los Angeles County — Second Interim Report. Committee on Smoke and Fumes. Western Oil and Gas Association, 510 West Sixth Street, Los Angeles 14, Calif. (1949). Copies free from Committee.

Reviewed by W. C. L. Hemeon, Engineering Director, Industrial Hygiene Foundation of America, Inc., Pittsburgh 13, Pa.

PROBABLY the largest technical effort in terms of dollars per year is being exerted in connection with the notorious Los Angeles smog problem which developed with the spectacular industrialization of that area during the past ten years. The oil refineries through their Western Oil and Gas Association have been supporting extensive work at the Stanford Research Institute, aimed at determining the nature and causes of Los Angeles smog which, from the standpoint of the "consumer" has two effects—occasional intense irritation of the eyes, and frequent haze markedly affecting visibility.

From time to time, reports circulated that the eye irritant had been identified. At one time it was thought to be finely divided elemental sulfur, at another, some substances whose effect was aggravated by finely divided oil mist; and, more recently, some organic peroxide(s) partly identified in smog.

In this report, it is concluded that none of these is responsible by itself, that it must be the effect of a number of contaminants in a mixture.

Substances whose concentration have been measured during smogs are: sulfur dioxide (0.1 p.p.m. (vol.)), ammonia (0.1 p.p.m. (vol.)), nominal sulfur trioxide (0.05 p.p.m. (wgt.)), aldehydes (0.15 p.p.m. (wgt.)). Others present, but whose concentrations have not been determined are: chlorides, carbon, ozone, hydrogen sulfide, vegetable debris, and many metallic elements.

Detailed analyses of particulate matter in the atmosphere are reported from chemical, spectrographic, and other physical studies.

Determination of gaseous contaminants involved the use of several types of samplers including freeze-out trains, water scrubbers, and SO_2 recorders. Analytical work has included use of the mass spectrometer.

Studies on visibility have resulted in development of concentration and particle size data in relation thereto; determination of the relationship between visibility and concentration of SO_2 at different relative humidities (it is concluded that SO_2 is not a significant factor in L. A. haze); similar studies (and conclusions) were made on NaCl fumes; development of a camera method for quantitative measurement of visibility.

This report provides interesting reading and valuable background for those concerned with this problem.

Personal Approach to Patent Practice

Patent Practice and Management for Inventors and Executives. Robert Calvert. Scarsdale Press, Scarsdale, N. Y. (1950) 371 pp. $5.00.

Reviewed by L. F. Marek, Arthur D. Little, Inc., Cambridge, Mass.

THIS well-prepared and refreshingly clear presentation of the salient features of the subject of patents should be well received in the private and corporate libraries of patent-conscious American business. The style is clear and direct and the reader is carried along, by the seemingly personalized approach.

The author has abandoned the case method so prevalent in writings on legal topics but has used case material in examples to illustrate his points throughout the book. The approach is entirely practical. The book obviously makes no pretense at being exhaustive in its treatment of the several aspects of securing and using patents and thus would not function as a last-resort reference in the resolution of questions dealing with the finer points of the subject. However, the treatment of the field is comprehensive.

This book should appeal alike to those whose duties on the one hand require administration of a patent portfolio and on the other the judicious fostering of a management policy as well as to those who make inventions, draft and prosecute patent applications, or direct the activities of technical teams dealing with research and development. A reading of the book should fill a long-felt desire on the part of many executives and inventors to know more of the technique of drafting and prosecuting patent applications, of the mechanics of patent-office procedure, and of the uses to which patents may be put.

The text material is divided into 30 main topics treated as chapters. Quotations, excerpts from decisions, tabular material and similar inserts are printed in smaller type and set in for easy characterization. Appropriate footnote references are conveniently given on the page where the material is used.

The author, now a practicing attorney in New York City, has personally experienced the pleasures and disappointments of the inventor.

For Upperclassmen in Chemical Engineering

Industrial Chemistry (Fifth Edition). E. Raymond Riegel. Reinhold Publishing Corp., New York. (1949) 1015 pp. $7.00.

Reviewed by V. T. Stewart, Professor, Chemical Engineering, Newark College of Engineering, Newark, N. J.

THE subject matter of this book follows the traditional pattern which seems most appropriate for books with this title. However, this fifth edition is an enlargement of 154 pages (nearly 20%) above the preceding edition. Of the 1015 pages, 832 are divided into 39 chapters, each of which deals with a single industry. Since a staggering amount of material has been compressed into the space allowed, the style is of necessity entirely descriptive or encyclopedic in nature.

This is essentially a textbook for use with upperclassmen in chemistry and chemical engineering courses. As such this edition has almost reached the maximum in size and in price. The field is enormous but the students' time is limited. With such concentrated instruction there is always danger of their acquiring a feeling of finality. But the author has dissipated any tendency of this kind by providing at the end of each chapter, a list of references, extensive enough to slow down the hurry-up boys.

Such a book can be examined by sampling only and this reviewer has selected the chapters on rubber and soap as representaitve. The one on rubber takes on the nature of journalism and rightly reflects the state of flux in which the industry finds itself. The treatment of *GR-S* is excellent. In fact, as I read the account, I found myself revisualizing a plant where I had an unusual entree. For nearly a century, the rubber industry operated on a traditional basis, but with the development of the automobile, the high-brow scientists and the scientific engineers moved in. Now they are in control. All of this development is adequately featured in this chapter.

The chapter on soap is much less exciting. To be sure, the newer developments are on the more scientific side and are consequently less obvious. The McBain-Vold work is not mentioned.

From page 832 on, the subject matter is different and deals with subjects which are accessory to the main topic. There are patents, instruments, machinery and a variety of metals. What, one may ask, is the value of an 11-page chapter on patents? Here brief introductions to this or that topic are the bane of the educational world.

The publisher advertises the work as one intended for the general reader. What *such* a one would be able to get from it is a mystery. However, to the worker in the chemical field, it is a mine of information.

You Know or Do You?

Who Knows—and What, Among Authorities, Experts and the Specially Informed. The A. N. Marquis Co., Chicago, Ill. (1949) 7⅛ x 10¼. 850 pp. $15.70.

Reviewed by Richard J. Francis, National Director of Society of Plastics Engineers, and a Licensed Chemical and Mechanical Engineer of Newark, Ohio, Member of the Steering Committee of Reinforced Plastics Division of Society of Plastics Industry.

BELIEVING that there is an everyday need for a reference work listing knowers, their specialties and conversancies, the A. N. Marquis Co. has published a volume titled "Who Knows—and What, *Among Authorities, Experts and the Specially Informed.*"

Purpose of "Who Knows" is to assist people with problems to locate quickly specialists who can help. This is accomplished with two cross-referenced lists: a subject index and a knower index. In the first are 35,000 different subjects ranging from Aardvark (a snoot-nosed burrowing, ant-eating, African mammal) to Zulu language which are keyed to names, addresses and biographical sketches of 16,000 experts qualified to deal with them.

This first edition is a reduction to book form of 55,000 replies to questionnaires sent to listees in "Who's Who," to members of several professional organizations, to writers and lecturers in specialized subjects and to research foundations.

In the preface the publishers point to the possibility of errors, both of omission and of commission, which creep into first editions and which can be corrected in later editions. Also, they point to the magnitude of this undertaking and to the problems involved in the judicious selection both of subjects and of knowers. They admit that any successful business man, engineer, lawyer or journalist—or any Ph.D. in writing a thesis—could rightly be considered an authority in his field. Arbitrarily they decided to avoid duplicating fields where directories now exist and to confine listings to subjects they felt might comprise the normal daily inquiry, plus men and women conversant with these subjects either as authorities or experts.

To the writer it seems that the unique features introduced into this book will make it a valuable reference tool to many individuals and organizations. Numerous chemical engineering and related subjects are listed and many members of A.I.Ch.E. are included in the knower index as authorities or experts.

The Scientist's Ready Reckoner. W. Roman. Published by Dr. W. Junk, The Hague, Netherlands. 142 pp.

THIS book is a mathematical compendium for aid to the analytical and laboratory chemist. It contains sections on Atomic weights, Higher multiples, Weights of molecules and radicals, Gravimetric factors, Titrimetric factors, Specific gravity for liquids, Temperature conversion tables, Four-figure logarithms and Five-figure logarithms.

The value of the book consists solely in its utility in bringing together under one cover mathematical tables of use to the chemist in the laboratory.

The Merck Manual. Merck & Co., Rahway, N. J. (1950) 1592 pp. $4.50 regular edition; $5.00 thumb-index edition.

THE eighth edition of the Merck Manual, Golden Anniversary Edition, has come off the press just recently. The new volume has the same format as the earlier familiar Merck manuals, well known to physicians, pharmacists, and other workers in the medical-pharmacal industries.

The new manual is 1600 pages in length, containing 338 chapters in Part I. This is the first revision since 1940 and new sections are on antibiotics therapy, the experiences and advances in medical science during World War II, and other data on vitamins, Cortisone, ACTH, etc.

The first printing of 75,000 copies was exhausted by advance orders and a new printing is now on the press.

Books Recently Published

Methyl Ethyl Ketone. Shell Chemical Corp., New York, N. Y. (1950) 130 pp.

THIS second edition is now available on letterhead request from Shell Chemical Corp., 500 Fifth Avenue, New York 18, or 100 Bush Street, San Francisco 6.

Molecular Spectra and Molecular Structure. 1. Spectra of Diatomic Molecules. Second Edition. Gerhard Herzberg. D. Van Nostrand Co., Inc., New York, N. Y. (1950) 658 pp. $9.75.

Chemical Analysis of Aluminum. Third Edition. Under direction of H. V. Churchill. Aluminum Research Laboratories, New Kensington, Pa. (1950) 150 pp. $1.00.

(More Marginal Notes on page 29)

This Simple Principle

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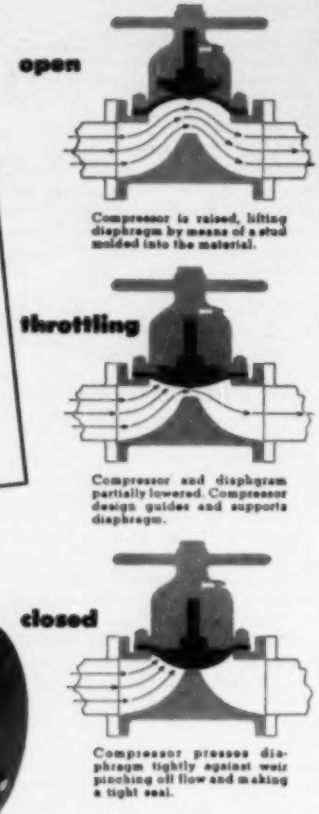
open
Compressor is raised, lifting diaphragm by means of a stud molded into the material.
throttling
Compressor and diaphgram partially lowered. Compressor design guides and supports diaphragm.
closed
Compressor presses diaphragm tightly against weir pinching off flow and making a tight seal.

● When it comes to valving hard-to-handle fluids, the simple pinch clamp principle of Hills-McCanna valves (see above) eliminates most ordinary valve troubles. There is no leakage, no packing and material handled cannot contaminate or be contaminated by the working parts. Hills-McCanna Saunders patent diaphragm valves are the answer to many of the most serious valve problems. Write for full details and ask for a copy of Catalog V-48. HILLS-McCANNA CO. 2438 W. Nelson Street, Chicago 18, Illinois.

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WHAT'S IN A NUMBER!

LEWIS C. HULLINGER

That rhetorical question, "what's in a name," and its implied negation do not preclude the possibility of something existing in a number. At least A.I.Ch.E. believes in the magic of number 10,000 for it's live and full of promise. His name is Lewis C. Hullinger, associated with Standard Oil Co. (Indiana) at Whiting, Ind., who is the 10,000th member of A.I.Ch.E.

Hullinger, not yet 30 years old, was studying chemical engineering at Ohio State University when his course was interrupted to the extent of one year's service in the U. S. Army and two years in the Marine Corps. While at Ohio State he served on the editorial staff of the Ohio State Engineer and was a member of the student chapter of A.I.Ch.E. Since graduation in 1947, Hullinger, who has been working with Standard in the process design division, decided recently to join A.I.Ch.E. "for closer contact with current developments in the chemical engineering field."

B. F. DODGE HONORED BY YALE ASSOCIATES

Eighty present and former students and Yale associates of Barnett F. Dodge, professor and chairman of the chemical engineering department at Yale University, New Haven, Conn., tendered him a surprise dinner June 3. This marked the 25th anniversary of Dr. Dodge's arrival at Yale and his former students and associates chose this occasion to express their appreciation of his active part in their preparations for careers and willing cooperation as a colleague. The group, together with a large number of former students who were not able to be present, presented him with photographic equipment for use in his hobby. The presentation was made by Dr. Harry A. Curtis, former chairman of the department at Yale University and now one of TVA's administrators.

Chemical Engineering Progress

DATA SERVICE

BULLETINS

1 • SOLENOID-OPERATED VALVES. Annin Co. describes a new series of electropneumatic solenoid-operated valves for control of corrosive and erosive fluids and high temperatures and pressures. The valve will control from a remote point, corrosive liquids such as sulfuric, nitric, various gases, up to 3000 lb./sq.in., and temperatures to 1000° F. Valve is actuated by the Annin Domotor Assembly which uses air pressure to open the valve which is held in a closed position by a spring. Fully described in the bulletin, the valves are available in sizes of ¾ in. to 2 in. and in various metals.

2 • SPECTROPHOTOMETER. A bulletin explaining technical details with a price sheet of Beckman Model B spectrophotometers is newly published by the National Technical Laboratories. The operating mechanism is explained, as well as various performance characteristics illustrated by charts of effective band widths and transmissions.

3 • COMPRESSOR. A two-stage air cooled class of compressors is described in a bulletin of the Joy Manufacturing Co. The new compressor comes in 11 sizes with operating capacities from 81 to 640 cu. ft./min., up to 125 lb. pressure using 15 to 125 hp. motors.

The compressor is air cooled, two-stage system. Charts show the capacities, dimensions, descriptions and illustrate the cylinder arrangement. Cutaway views show the sections and photographs illustrate the oil cooling, models and other construction features such as bearings, valves, pistons, etc.

4 • WATER SEEPAGE CONTROL. For controlling seepage through brick, concrete, stucco, etc. walls, either above or below grade, interior and exterior, the Prufcoat Laboratories, Inc., have a bulletin explaining a new liquid formulation of special synthetic resins which will seal masonry material against such water seepage. Bulletin illustrates a test for permeability of masonry material, describes the three types available. Designed for either painting or spraying.

5 • DEMINERALIZATION. For the production of pure water, Barnstead Still & Sterilizer Co. printed a new bulletin on demineralizers. The catalog tells the story of the production of water for electroplating, cosmetics, pharmaceuticals, ice manufacturing, storage battery, etc., through the operation of cation-anion exchangers. The catalog explains the functions of the exchangers, describes the installations in various plants for various purposes, and illustrates all of the equipment available from 30 gal./hr. up to 1000 gal./hr. automatically controlled.

6 • 7 • ELECTRONIC CALCULATIONS. Two publications from International Business Machines Corp. explain the fundamentals of electronic calculation. The first bulletin, (6) "Electrons at Work," describes briefly the operation of the electronic tube and its application to electronic calculators and business machines. The second publication, (7) "Fundamentals of Electronic Calculation," discusses the fundamentals of preparing material for an electronic calculator. It shows the proper way to set up a formula for the calculator, tells what problems the I.B.M. calculator will solve, and then gives a complete story of a problem solved on pile driving.

8 • RACKS. A new and comprehensively illustrated catalog on racks and the typical rack applications that can be made with the Unistrut. The Unistrut metal structure comes in five different sizes and is generally available in 10-ft.–20-ft. lengths. The catalog illustrates the types of channels, method of building racks, and adjusting them for use in chemical storage to make pallets, skid racks, etc. Can be made into any type of rack for any purpose.

9 • CONVERTORS. The Patterson-Kelley Co., Inc., describes a line of convertors for use with hot water heating systems. Convertor is a shell and tube condenser, the steam entering the shell and condensing on the tubes to heat the water for the hot water system. Catalog describing units also has capacity table which shows the gallons of water heated per hour for specific temperature dif-

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ferences. Also shows pressure drop in heat exchanger; and dimensions of all the convertors.

10 • RESEARCH MANAGEMENT. For executives in research administration, Arthur D. Little, Inc., has a selected bibliography of books and articles on management of industrial research. The pamphlet was prepared for members of the Arthur D. Little staff but is being made public by the group because of the interest in programs. Contains sections on general references, background, organization, control of research programs, technical economics, etc.

11 • GLASS COLUMNS. A price folder of the Glass Engineering Labs. gives a complete new listing of prices. Perforated glass plate columns from ¾-in. to 4-in. diameters, packed columns ¾-in. to 1½-in. diameters, solenoid still heads, etc.

12 • TITRILOG. For recording the concentration of sulfur compounds in a gas stream or atmosphere, the Consolidated Engineering Corp. describes in a 4-page bulletin, the new Titrilog. Schematic diagram shows how the instrument cell and amplifier works; gives details on sensitivity, which is 0.5 grains of mercaptan sulfur/100 cu. ft. of gas. Operation is continuous and gives recording of results.

EQUIPMENT

23 • AIR HEATER. An air heater for industrial ovens and dryers, which is available in capacities of from 250,000 B.t.u–2,000,000 B.t.u./hr. is a new product of the W. S. Rockwell Co. The unit provides a uniform forced circulation of heated air up to 600° F., but it may be installed on ovens and dryers already heated by internal burners. the unit acting to recirculate the heated air to give uniform heating and control. Used for all industrial operations where drying or baking is accomplished by hot air circulation.

24 • MOTOR COOLER. For cooling large, enclosed motors, the Elliott Co. is in production with a Unit-Cool'd finned tube air-to-air heat exchanger designed to cool the air which is already within the motor. A fan draws air from outside the motor through the heat exchanger tubes and out the front of the motor enclosure. Air within the motor is passed within the finned tubes. cooled and recirculated. For 300 to 4000 hp. units.

25 • PROTECTIVE MASK. For repairing acid line breaks and on other jobs where complete face, head and neck coverage is required, Industrial Products Co. has a new acid mask. The new unit is manufactured with an aluminum frame, to which is attached a sealed hood of clear vinylite.

26 • KARBATE PIPE THREADER. For threading impervious graphite pipe, national carbon division of Union Carbide & Carbon Corp. has developed a new hand-threading tool. The new hand unit eliminates a lathe operation, is portable, and makes it possible to cut Karbate pipe on the job.

27 • HAMMER MILL. A heavy duty industrial hammer mill in two models, is in new production by the Daffin Manufacturing Co. Powered by diesel, gasoline or electric motors, the new mills incorporate a finger feed roll to handle roughage and fibrous materials. Speed changes may be adjusted instantaneously to allow for the materials being ground.

28 • VENTILATING FANS. The Moore Co. has introduced a new series of ventilating fans. Furnished in diameters of from 3- to 5-ft., capacities going from 11,000 to 30,000 cu.ft./min. They are of the direct-drive type, the motor being completely enclosed within the hub and housing. No outside air is circulated through the motor enclosure, all cooling being accomplished by heat transfer through the metal of the hub and housing. Bulletin available.

29 • LIQUID LEVEL TRANSMITTER. A new transmitter using buoyant force on a partly immersed cylinder, with a sensitivity of one part in 14,000, for measuring liquid level, has been introduced by the Brown instruments division of Minneapolis-Honeywell Regulator Co. Transmitter can be used for differences in level ranging from 14 to 120 in. and for liquids of various specific gravities. Working pressures as high as 600 lb./sq.in. and temperatures up to 450° F. are possible.

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30 • ELEVATOR CHAIN LINK. For use on chains on bucket elevators, the Beaumont Birch Co. has designed a link which features a new design with more metal on the side of barrel making contact with the sprocket or traction wheel. The link is available in 350 Brinell steel and test installations show a life of twenty times that of malleable iron links.

31 • STEAM-JACKETED VALVE. For use on rotary sulfur vaporizers in the sulfite pulp industry, the G. D. Jenssen Co., Inc., has a new steam-jacketed flow control valve, which is also adaptable for flow control on thermoplastic materials such as asphalt, wax, resins, etc. Valve body steam-jacketed, chrome-nickel seat. The valve is actuated by a flanged diaphragm motor. Available in ½- and ¾-in. sizes.

32 • DRY MIXER. For precision in mixing dry, free-flowing materials, the MacLellan mixer, a product of The Anglo American Mill Sales Co., a rotating sectionalized drum mixer, is available in sizes from 5 quarts to 160 cu. ft. For laboratory sampling as well as plant production.

33 • SMALL AFTERCOOLER. For cooling and drying compressed air, Jas. A. Murphy & Co., Inc., have a new aftercooler for use on the small air compressor. The small unit handles up to 20 cu. ft., and the larger size up to 50 cu. ft.

34 • LEAD SHIELD. A new portable lead shield designed for use in carrying radio isotopes in standard 30 cc. bottles, is new with the Atomic Instrument Co. Aluminum inner and outer shells provide a minimum lead wall thickness of 1 in. in all directions.

35 • ELECTRONIC RELAY. For a power control of delicate contact-making instruments, thermoregulators, etc., the American Instrument Co., Inc., has a new electronic relay. It can be used to actuate motors, valves, alarms, etc. Control leads up to 2000 ft.

36 • DYNEL FILTER CLOTH. For a chemical resistant filter fabric, Filtration fabrics division of Filtration Engineers, Inc., has now produced a fabric out of Dynel (vinyon-N). The fabric is made of spun-staple fiber, making it easy to seal the press without excessive rim pressures. Recommended for acid use, and also for resistance to alkalis, bacterial action and a variety of organic solvents.

37 • PILOT PLANT SHELL BLENDER. A pilot plant twin-shell blender available in two sizes, 4 and 8 qt., a development of The Patterson-Kelley Co., Inc. Will give results as to efficiency of blending, timing, and capacity to be expected on large size production units. The V-shaped shells are made of heavy, transparent plastic so that a visual check can be made on the blending operation. Uses a 1/20 hp. motor and is driven at 32 rev./min.

38 • PLASTIC PAIL. An unbreakable, styrene copolymer pail for transportation of acids and alkalis is new with the American Hard Rubber Co. Special designs have been incorporated into it to insure pouring without splashing.

39 • STUFFING BOX PACKING. For use in stuffing boxes where resistance to chemical attack is necessary, United States Gasket Co. is offering cone-type Teflon packing. The Teflon withstands temperatures up to 550° F. and requires no additional lubrication. Available with adapter for either a square end or chamfered end stuffing box.

40 • ELECTRON MICROSCOPE. Complete information on the new size RCA electron microscope. It is a 30-in. table model, expected to sell for $6000. Will provide useful magnifications up to 50,000 diameters by photographic enlargement with direct magnification in the instrument up to 6000 diameters.

41 • LEVELIMETER. For measuring liquid level changes Fischer & Porter Co. has a new displacer-buoy levelimeter instrument. By suitable dimensions of the displacer-buoy components, the total liquid level change, whatever it may be, is caused to produce a total buoy travel of 5 in. This matches the standard travel of F & P instrument transmitters. An electric impedance bridge is used to transmit the level readings to exhibiting instruments.

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CHEMICALS

45 • TIN PLATING. A technical bulletin on electrotinning from the Metal & Thermit Corp., gives suggested bath formula and performance data on both potassium and sodium stannate plating solutions. In addition, it contains instructions for analyzing and controlling the bath and has a section devoted to the new high speed tin anodes. Contains a history of alkaline tin plating, plus information on the advantages.

46 • EXTRACTION SOLVENTS. A pamphlet of the American Mineral Spirits Co. on pentane, isohexane, hexane, isopheptane and heptane. Used in solvent extraction of vegetable, animal oils, etc. Gives physical specifications for the various solvents.

47 • ISOCYANATE ADHESIVES. A technical bulletin from Monsanto Chemical Co. reviews the development and present practice, both German and American, of isocyanate-based adhesives. The pamphlet explains the mechanism, chemistry, materials available; gives examples of German practice, application, American practice, plus formulations that are used in the fields. Reviews patents, etc.

48 • CORTISONE. A fascinating story from Merck & Co., Inc., on Cortisone, used in the treatment of arthritis and other diseases. Merck is now in production and the report gives the history, synthesis and background story behind the development of this drug.

50 • PARAPLEX RESINS. A 24-page booklet by resinous products division of Rohm & Haas Co. on the Paraplex P series resins—solutions of polyester resins in styrene. The booklet gives the physical properties of the liquid resins, viscosity, mechanical tests, electrical tests, etc.; uses of Paraplex reinforced with fiber glass, with paper reinforcements, compounding of the resins, catalyst accelerators, curing, etc. A complete data book on these materials.

51 • HANDLING PHOSPHORIC ACID. Equipment and procedures for handling 75% phosphoric acid in tank-car quantities, are described in a pamphlet by the Monsanto Chemical Co. In line with its other pamphlets on handling tank-car products, it gives physical properties, tells about the safety hazards, describes the equipment for handling storage tanks, rubber-lined pipe, pumps, etc. Gives procedures for unloading tank cars and shows methods of piping tank cars to storage tanks.

52 • CHLORINATING WATER. A bulletin on the chlorine treatment of municipal water, which summarizes present-day processes and equipment, is a new publication of the Fischer & Porter Co. A flow sheet shows a typical water treatment system. The text explains the various chlorination practices, and illustrates the use of F. & P. equipment to do this.

53 • POLYCLAD. A data sheet from Carboline Co., gives physical specifications, uses, corrosive tests, etc., for Polyclad, a polyvinyl chloride coating system. Used to protect surfaces of metals, concrete, wood, insulation, etc. Table gives data on corrosion tests.

54 • CHROMIUM CHEMICALS. Diamond Alkali Co. publishes a pamphlet on chromium chemicals which shows their use in 17 different industries—in leather tanning, giving information and analysis of chrome-tanning liquors, determining chromium in leather, in dyes and intermediates, textiles, etc. Methods of analyzing chromates given, plus data on Baumé of chromate solutions, etc.

55 • WEED CONTROL. An integrated series of booklets describing uses and advantages of controlling weeds or chemical sprays has been published by Monsanto Chemical Co. (a) Controlling Weeds with Chemical Sprays, describes the chemicals used for weed control and how they are applied. (b) Weed Control on Right of Ways goes into the reaction of plants to certain weed killers and discusses weed eradication in tank farms, yards, storage dumps, etc. (c) Is on the formulation of 2,4-dichlorophenoxyacetic acid, and its chemical and physical characteristics, formulating dusts, description of mixing and spraying equipment, solubility guide, etc. (d) Is on the formulation of Santobrite, a sodium pentachlorophenate. (e) Is on the formulation of Santophen 20, a pentachlorophenol. Other booklets are available from the company on agricultural weed control.

56 • SOLVENTS. A data book on solvents manufactured by American Mineral Spirits Co. gives a table on industrial use of solvents and types to use, physical data on industrial petroleum naphthas, petroleum solvents and hydrocarbons, and details comparative evaporation rates of petroleum solvents, etc.

57 • MBDSA. The chemical division of the Koppers Co., Inc., has a new technical bulletin describing the physical and chemical products of meta-Benzenedisulfonic acid (MBDSA). The compound has been suggested for use in the electroplating of certain metals, as an intermediate for dyestuffs, pharmaceuticals, and photographic chemicals, and as a catalyst for esterifications. The bulletin has all technical information, including structure, chemical reactions, literature references, etc.

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MARGINAL NOTES

(Continued from page 27)

"Frankly Vocational Outlook"

Gas Transportation System Calculations. Benjamin Miller. Moore Publishing Co., Inc., New York. (1949) 226 pp. $7.50.

Reviewed by Ben M. Holt, The Ralph M. Parsons, Co., Los Angeles 14, Calif.

THIS book consists of a series of 40 articles which appeared in *Gas Age* during 1947 and 1948. It is written in four sections which cover (1) The Flow of Gas in Pipes, (2) The Specification, Inspection, and Testing of Pipe for Gas Lines, (3) The Compression of Gas, and (4) The Economics of Gas Transportation.

As the writer states, it has a "frankly vocational outlook," and therefore is of primary interest to those engineers working in the field of gas transportation.

The first section, dealing with flow of gas in pipes, presents the basic flow formula as well as three empirical formulae for the solution of various types of flow problems. These formulae are given without derivation or a discussion of the probable accuracy. However, it is apparent that the use of these formulae greatly simplify calculations in systems involving compressible fluids, and enable the engineer to calculate easily the relationships between flow, pressure drop, and pipe diameter. The author goes to unnecessary lengths in presenting solutions to his numerical examples by the use of logarithms. In most cases the answers alone could have been given and readily checked by the reader with a slide rule. Methods of correcting his basic calculations for compressibility, nonisothermal flow, kinetic energy changes, and change in elevation are given, and the section includes a discussion of efficiency tests, series and parallel flow, nonturbulent flow and graphical computations.

The second section deals with specification, inspection, and testing of pipe for gas lines.

The third section deals with the compression of gas. The subject is introduced by a discussion of the concepts of entropy, enthalpy, reversible processes, isothermal and adiabatic compression, from which are developed equations to calculate compression requirements for actual gases in actual piston compressors. Deviation of actual gases from perfect gas laws is discussed more thoroughly than in the first section. Methods of calculating entropy and enthalpy charts are given.

The last section deals with the economics of pipe-line transportation.

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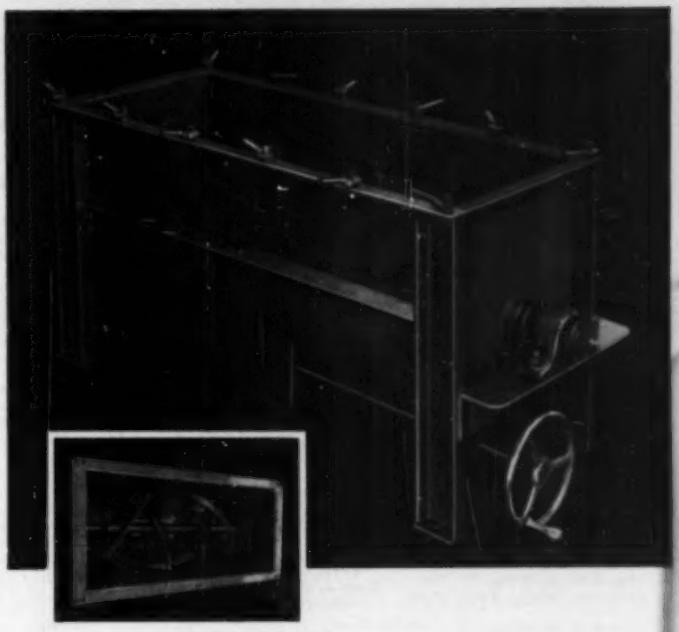

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Read Spiral Ribbon Blenders are built with batch capacities of from 1 to 500 cu. ft. Special units are custom-built for larger capacities. Models can be supplied for operation under pressure or full vacuum, and may be equipped with temperature controlling jackets. Structural steel legs can be supplied in various heights to suit operating conditions.

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CANDIDATES FOR MEMBERSHIP IN A. I. Ch. E.

The following is a list of candidates for the designated grades of membership in A.I.Ch.E. recommended for election by the Committee on Admissions.

These names are listed in accordance with Article III, Section 7, of the Constitution of A.I.Ch.E. which states:

Election to membership shall be by vote of the Council upon recommendation of the Committee on Admissions. The names of all applicants who have been approved as candidates by the Committee on Admissions, other than those of applicants for Student membership, shall be listed in an official publication of the Institute. If no objection is received in writing by the Secretary within thirty days after the mailing date of the publication, they may be declared elected by vote of Council. If an objection to the election of any candidate is received by the Secretary within the period specified, said objection shall be referred to the Committee on Admissions, which shall investigate the cause for such objection, holding all communications in confidence, and make recommendations to the Council regarding the candidate.

Objections to the election of any of these candidates from Active Members will receive careful consideration if received before *August 15, 1950*, at the Office of the Secretary, American Institute of Chemical Engineers, 120 East 41st St., New York 17, N. Y.

APPLICANTS FOR ACTIVE MEMBERSHIP

Joseph Allerton, *Sayville, N. Y.*
Norman L. Amend, *Kenmore, N. Y.*
Victor N. Antaki, *Pocatello, Idaho.*
W. A. Bain, Jr., *New York, N. Y.*
Armand Raoul Boucher, *Louisville, Ky.*
R. J. Brosamer, *Bartlesville, Okla.*
Ralph W. Brown, *East St. Louis, Ill.*
Frederick Calvert Brunner, *San Gabriel, Calif.*
Ardeo Causey, *Baton Rouge, La.*
James A. Champley, *Charleston, W. Va.*
Clarence L. Crawford, *Oakmont, Pa.*
Joe Cresce, *Nitro, W. Va.*
Alwien Dierl, *Pittsburgh, Calif.*
Jacob A. Gaudino, *Rochester, N. Y.*
C. C. Haws, Jr., *Oak Ridge, Tenn.*
Rolf H. Hemmerich, *New York, N. Y.*
Desmond B. Hosmer, *Belleville, Ill.*
Paul A. Kannapell, *Webster Groves, Mo.*
James O. Kelly, *Shawinigan Falls, Que., Canada.*
Gordon Kiddoo, *Amarillo, Tex.*
George F. Kirby, *Baton Rouge, La.*
W. E. Kuhn, *Scarsdale, N. Y.*
Alton I. Lockhart, Jr., *Bloomfield, N. J.*
Robert M. McAdam, *Wilmington, Del.*
Henry J. Ogorzaly, *New York, N. Y.*
Joseph D. Parent, *Chicago, Ill.*
Henry B. Peterson, *Washington, D. C.*
Harry Pforzheimer, Jr., *Willoughby, Ohio.*
Norman W. Ryan, *Salt Lake City, Utah.*
Davis Ayres Skinner, *Compton, Calif.*
Milton E. Smith, *St. Paul, Minn.*
Robert C. Smith, Jr., *Charleston, W. Va.*
John B. Sutherland, *Burlingame, Kan.*
Raife G. Tarkington, *Rochester, N. Y.*
John K. Ward, *Lemay, Mo.*
W. C. Weber, *Westport, Conn.*
George White, Jr., *New York, N. Y.*
Eugene P. Whitlow, *Evansville, Ind.*

APPLICANTS FOR ASSOCIATE MEMBERSHIP

Paul Blunt, *Bellerose, N. Y.*
Robert D. Gotwals, *Wilmington, Del.*
William J. Govan, *Los Angeles, Calif.*
Chas. H. Jenkins, *Denver, Col.*
Thomas F. Moschetto, *Highland, N. Y.*
Charles Allen Walker, *Hamden, Conn.*

APPLICANTS FOR JUNIOR MEMBERSHIP

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W. J. Baldridge, *Phillips, Tex.*
Walter Frederick Ball, *Port Arthur, Tex.*
David J. Barsa, *El Paso, Tex.*
Robert E. Bilger, *Monsanto, Ill.*
Bernard I. Bratter, *Los Angeles, Calif.*
Robert P. Cahn, *Elizabeth, N. J.*
R. J. Cox, *Laramie, Wyo.*
Charles D. Darwin, F.P.O., *New York, N. Y.*
H. William Day, *El Monte, Calif.*
Carl L. Dismukes, Jr., *Orange, Tex.*
Wesley T. Dorsheimer, *Sharon, Mass.*
C. Donald Everson, *Lawrenceburg, Ind.*
David M. Falk, *Army Chemical Center, Md.*
Howard L. Grimmett, *San Francisco, Calif.*
Arthur Hasenkamp, *Denver, Col.*
Bernard Jacknin, *Kearny, N. J.*
Clifford A. Junghans, *Richland, Wash.*
James A. Kapnicky, *Morgantown, W. Va.*
Ivan Kenis, *Dayton, Ohio.*
Evan C. Kovacic, *Chicago, Ill.*
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Lillian G. Murad, *Douglaston, N. Y.*
Ernest W. Neben, *Rochester, N. Y.*
Rajendra Paul, *Brooklyn, N. Y.*
Kenneth W. Perry, *Caseyville, Ill.*
Bruno H. Pilorz, *Houston, Tex.*
Roy Walter Pneuman, *Brooklyn, N. Y.*
C. C. Reddy, *Columbus, Ohio.*
William E. Repschleger, *Texas City, Tex.*
Robert R. Rhodes, *Harrison, N. J.*
Harold Rounds, *Syracuse, N. Y.*
Dale L. Salt, *Salt Lake City, Utah.*
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Charles W. Shartzer, Jr., *Norristown, Pa.*
Claude R. Smith, *Lake Charles, La.*
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SECRETARY'S REPORT

S. L. TYLER

The Council of the Institute met at the New Ocean House, Swampscott, Mass., on May 28 and handled a full and complete agenda.

A report was received from the Public Relations Committee, J. H. Perry, Chairman, telling of the work accomplished to date and future plans.

Anticipating the Fiftieth Anniversary of the Founding of the Institute a special committee was set up to consider the preparation of a Fifty-Year History of the Institute.

A report was also received from the Student Chapters Committee, J. S. Walton, Chairman. As a result of suggestions made by the Committee, the Council acted favorably upon recommendations for further direct contact with student chapters by Officers and Directors of the Institute, and the awarding of a two-year subscription to *Chemical Engineering Progress* to that student chapter member in Junior status who was given the student scholarship award; also to increase the Student Chapters Committee budget by $100 to enable it to provide prizes for the papers presented at student chapter regional meetings.

C. G. Kirkbride, Chairman of the Membership Committee, reported on the activities of his Committee.

He was reappointed Institute representative on the Engineers' Council for Professional Development for a three-year term begining October, 1950.

N. A. Shepard was appointed Institute representative on the division of engineering and industrial research of the National Research Council to succeed G. O. Curme, whose three-year term expired June 30, 1950.

J. C. Elgin was reappointed Institute representative on the division of chemistry and chemical technology of the National Research Council, for a three-year term beginning July 1, 1950. His first term expired June 30.

Report was received from the Chemical Engineering Education and Accrediting Committee covering activities for the first part of the year and it was voted that the Engineers' Council for Professional Development be advised of the actions taken. No publicity, however, can be given to these actions until the latter part of 1950.

Actions of the Executive Committee for the month of June as a result of mail ballot sent out on June 8 included the election to membership as indicated of all those applicants whose names were listed in the May, 1950, *Chemical Engineering Progress*.

The following were appointed as student chapter counselors: L. W. Gleckman at the University of Delaware to succeed S. A. Guerrieri; J. N. Addoms at the Massachusetts Institute of Technology to succeed W. H. McAdams; H. P. Simons at West Virginia University to succeed W. A. Koehler.

Two elections to membership were rescinded because no word was received from the applicants.

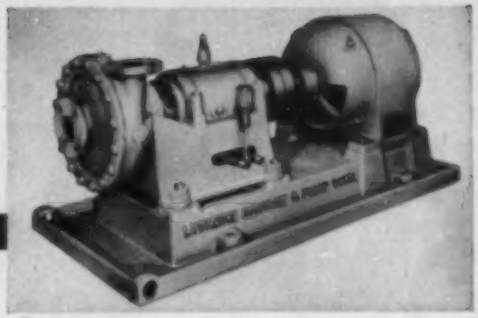
A few late appointments were made to Committee personnel. Resignations were received and accepted from eight Junior members.

DUNNING, DEAN ENGINEERING AT COLUMBIA

John Ray Dunning, professor of physics, scientific director of Columbia University's cyclotron at Irvington-on-Hudson, New York, has been appointed dean of the school of engineering at Columbia. The announcement was made recently by Dwight D. Eisenhower, president.

Dr. Dunning succeeds Dean James K. Finch who retired June 30 as dean but who will continue to teach resuming the chair of the Renwick professor of civil engineering, which he formerly held. According to the announcement Dr. Dunning's appointment brings to the position "a scientist and administrator whose activities have included both the fields of pure science and engineering."

Lawrence Process Pump



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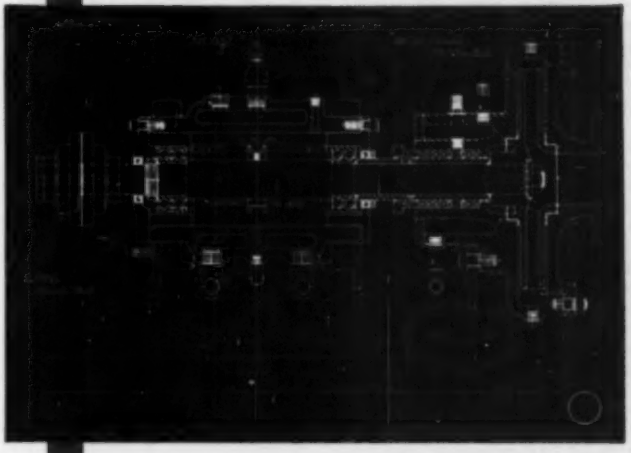

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LOCAL SECTION NEWS

IN ATTENDANCE AT ST. LOUIS ONE-DAY MEETING

From left to right: T. H. Chilton, Du Pont Co., and Vice-President A.I.Ch.E.; D. H. Tilson, Aluminum Ore Co.; W. T. Nichols, Monsanto Chemical Co., and Director A.I.Ch.E.; L. E. Stout, Washington University; F. J. Curtis, Monsanto Chemical Co., and Past President A.I.Ch.E.; J. W. McCrackin, Monsanto Chemical Co., and Chairman St. Louis Section A.I.Ch.E.; B. E. Thomas, Monsanto Chemical Co., and C. W. Swartout, Mallinckrodt; S. L. Lopata, Process Engineering and Equipment, Symposium Chairman.

ST. LOUIS

This section sponsored a one-day meeting on May 5 at the De Soto Hotel, St. Louis, at which two symposia were presented, namely, "Careers in Chemical Engineering," and "Unit Processes." Registration totaled 366 of which 122 were junior and senior chemical engineering students and the remainder active members and guests.

Dr. L. E. Stout, dean of the school of engineering at Washington University, presided over the morning session and W. T. Nichols, director of the general engineering department of Monsanto Chemical Co., presided in the afternoon.

Speakers and the titles of their talks and papers were listed in April issue of Chemical Engineering Progress, p. 41.

SOUTHERN CALIFORNIA

This section cooperated with the University of California at Los Angeles, department of engineering, on June 16, in presenting Dr. O. A. Hougen, professor of chemical engineering, University of Wisconsin, in one of an Engineering Series of Public Lectures. Dr. Hougen's subject was "Applied Kinetics of Catalytic Reactions." His lecture illustrated the importance and application of chemical kinetics in minimizing the costs of process development, design, and operation.

The monthly dinner meeting was held June 20, 1950, at Scully's Cafe in Los Angeles with 110 members and guests present. Howard G. Vesper, president, California Research Corp., was the guest speaker, and his subject was "Management and the Engineer." He pointed out the engineer's increasingly important role, not only in strictly technical activities, but also as a part of management.

Reported by William J. Baral

COLUMBIA VALLEY

This section, with headquarters in Richland, Wash., has held two meetings recently. At one of them Dr. J. A. Hall, director of the Pacific Northwest Experiment Station of the U. S. Department of Agriculture Forest Service, spoke on "Alcohol from Wood."

More recently, Prof. T. B. Drew, head of the department of chemical engineering at Columbia University, discussed the uncertainties involved in the evaluation and use of individual film mass-transfer coefficients, in a talk entitled "The Indeterminate H.T.U."

Reported by George Sege

OKLAHOMA

At a recent meeting at the McKinley School auditorium, Bartlesville, Bruce Bates of Phillips Petroleum Co. gave a 5-minute talk entitled, "The Engineer and Economics." Harry Eells of Shell Oil Co., Tulsa, showed two color sound motion pictures called "Pipelines," and the other, "Refining Oil for Energy."

Emil Malick, aviation technologist for Phillips Petroleum Co., spoke at a prior meeting. His subject was entitled "Jet Fuels and Engines."

Reported by G. E. Hays

NEW YORK

The traditional "Ladies Night" meeting of this section was held June 15, at the Brass Rail Restaurant on Fifth Avenue. More than 50 members and their wives attended and heard L. F. Livingston, manager of the extension department of the Du Pont Co., speak on the subject, "Progress in Better Living."

Mr. Livingston built his talk about the development of household articles out of many of the newer plastic materials. Illustrating his talk with a collection of numerous plastic items, the speaker stressed the fact that accomplishments in this field have been made possible by a close working cooperation between the basic resin producers and the many fabricators who convert the resins into articles usable in everyday life.

Reported by R. L. Demmerle

TULSA

The June meeting featured two brief talks by Junior members. These talks were presented in competition for the 1950 Cecil Trophy. This trophy is presented annually by L. K. Cecil of Infilco, Inc., for the best paper presented by a Junior member.

W. R. Seuren, assistant to the vice-president of manufacturing and research, Deep Rock Oil Corp., discussed "Preparation of Effective Personnel Résumés."

"A Brief Survey of Modern Physics" was presented by Myron B. Kratzer of Stanolind's research department as the second talk.

The meeting was held in Lorton Hall at the University of Tulsa, June 14.

Approximately 30 members and guests attended the meeting.

The May meeting of this section, held in Lorton Hall on the University of Tulsa campus, featured a talk by L. K. Cecil on one of the city's pressing problems, that of adequate sewage disposal facilities.

Mr. Cecil's talk covered the background of the problem and primary and complete treatment plants.

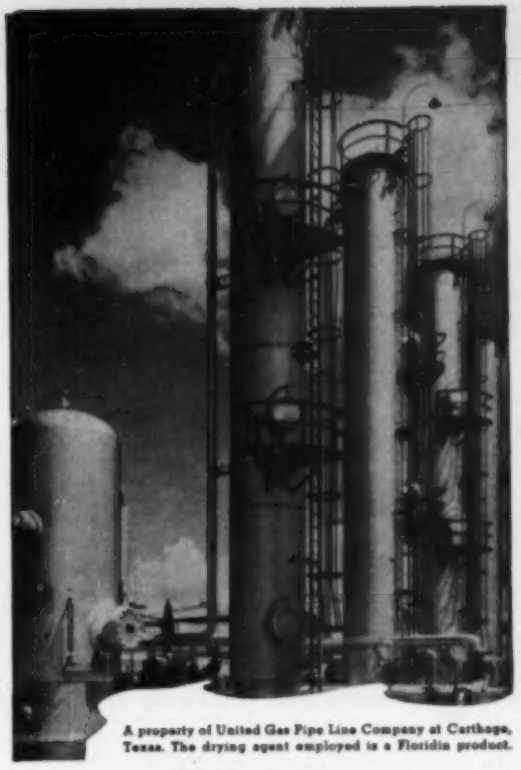
Forty-two members and guests were in attendance.

Reported by T. Q. Eliot

OHIO VALLEY

This section held a meeting June 5 at Meier's Winery, Silverton, Ohio. This meeting was a social affair with wives and other invited guests present. The program included an inspection trip through the winery.

Reported by A. C. Greber



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Chairman of the A.I.Ch.E. Program Committee

George E. Holbrook

Room 7406 Nemours Bldg.,
E. I. du Pont de Nemours & Co.,
Wilmington, Del.

MEETINGS

Regional — Minneapolis, Minn., Radisson Hotel, Sept. 10-13, 1950.

Technical Program Chairman: E. L. Piret, Minnesota Mining & Mfg. Co., Minneapolis, Minn.

Annual—Columbus, Ohio, Neal House, Dec. 3-6, 1950.

Technical Program Chairman: John Clegg, Battelle Memorial Institute, Columbus, Ohio

Regional — White Sulphur Springs, W. Va., The Greenbrier, March 11-14, 1951.

Technical Program Chairman: Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

Regional—Kansas City, Mo., Hotel Muehlebach, May 13-16, 1951.

Technical Program Chairman: Walter W. Deschner, J. F. Pritchard Co., Kansas City, Mo.

Annual — Atlantic City, N. J., Chalfonte-Haddon Hall Hotel, Dec. 2-5, 1951.

SYMPOSIA

Indoor vs. Outdoor Plant Construction

Chairman: J. R. Minevitch, E. B. Badger & Sons Co., 75 Pitts St., Boston, Mass.

Meeting—Minneapolis, Minn.

Quantitative Economics in Estimation of Risk Factors in Capital Ventures

Chairman: Mott Souders, Shell Development Co., 100 Bush St., San Francisco, Calif.

Meeting—Minneapolis, Minn.

Applied Reaction Kinetics

Chairman: R. H. Wilhelm, Princeton (N.J.) University

Meeting—Minneapolis, Minn.

Chemical Engineering in Food Industries

Chairman: W. L. Faith, Corn Products Refining Co., Argo, Ill.

Meeting—Minneapolis, Minn.

Phase Equilibria

Chairman: W. C. Edmister, Carnegie Inst. of Tech., Pittsburgh, Pa.

Meeting—Minneapolis, Minn.

What Should You Know About Management?

Chairman: L. P. Scoville, Jefferson Chemical Co., Inc., 711 Fifth Ave., New York 22, N. Y.

Meeting—Minneapolis, Minn.

Air and Water Pollution Control

Chairman: Richard D. Hoak, Mellon Institute of Industrial Research, University of Pittsburgh, Pittsburgh, Pa.

Meeting—Columbus, Ohio

Relationship Between Pilot-Scale and Commercial Chemical Engineering Equipment

Chairman: Walter E. Lobo, The M. W. Kellogg Co., 225 Broadway, New York, N. Y.

Meeting—White Sulphur Springs, W. Va.

Chemical Engineering in Glass Industry

Chairman: F. C. Flint, Hazel-Atlas Glass Co., Washington, Pa.

Meeting—Not scheduled.

Processing of Viscous Materials

Chairman: W. W. Kraft, The Lummus Co., 420 Lexington Ave., New York, N. Y.

Meeting—Not scheduled.

Authors wishing to present papers at a scheduled meeting of the A.I.Ch.E. should first query the Chairman of the A.I.Ch.E. Program Committee, George E. Holbrook, with a carbon copy of the letter to the Technical Program Chairman of the meeting at which the author wishes to present the paper. Another carbon should go to the Editor, F. J. Van Antwerpen, 120 East 41st Street, New York 17, N. Y. If the paper is suitable for a symposium, a carbon of the letter should go to the Chairman of the Symposia, instead of the Chairman of the Technical Program, since symposia are not scheduled for any meeting until they are complete and approved by the national Program Committee. Before authors begin their manuscripts they should obtain from the meeting Chairman a copy of the Guide to Authors, and a copy of the Guide to Speakers. The first book covers the preparation of manuscripts, and the second covers the proper presentation of papers at A.I.Ch.E. meetings. Presentations of papers are judged at every meeting and an award is made to the speaker who delivers his paper in the best manner. Winners are announced in *Chemical Engineering Progress*, and a scroll is presented to the winning author at a meeting of his local section. Since five copies of the manuscript must be prepared, one should be sent to the Chairman of the symposium and one to the Technical Program Chairman of the meeting, or two to the Technical Program Chairman if no symposium is involved and the other three copies should be sent to the Editor's office. Manuscripts not received 70 days before a meeting cannot be considered.

KANSAS CITY

To wind up a season of activities which included the formal installation of the Kansas City group, this section held its spring social function June 9, a dinner-dance, at the Rock Wood Country Club in Independence, Mo.

The last dinner-technical session of the 1949-50 season was held at the Plaza Bowl Green Room on May 16. The speaker was L. T. Kiefer of Great Lakes Carbon Corp., who spoke on the subject "Filtration and Filter Aids." Mr. Kiefer discussed various types of filter aids available and the advantages and possible use of each.

Reported by I. E. Miller

SOUTH TEXAS

The May 19 meeting of this section began with an inspection trip through the plant of the Consolidated Chemical Industries at Harrisburg (Houston), Tex. C. C. I. is one of the area's two largest producers of all grades of sulfuric acid and a group of 51 toured the plant examining the sulfuric acid and associated fertilizer facilities.

The section had as its guests for the evening the members of a party of French chemical engineers who are visiting the United States as guests of the Economics Operations Administration. These men are studying the petrochemical industries of the U. S. After dinner Jean Louis Bergeron, assistant department manager, production and marketing of petrochemicals, Shell Saint-Gobain, Paris, discussed the present status of the French chemical industry and its place in the general French economic scheme. At the dinner meeting 78 members were present.

Reported by G. T. McBride, Jr.

STATE COLLEGE CHAPTER

The formal installation of a student chapter of the A. I. Ch. E. was held at a dinner meeting in the State College Hotel, State College, Pa., May 27.

T. H. Chilton, Vice-President of the Institute, gave an address on "Careers in Engineering." Dr. Chilton presented the charter to Robert I. Miller, newly elected president of the student chapter. Other officers are:

Vice-President.....Philip Armstrong
Secretary.....J. D. Soltis
Treasurer.....J. H. Sinfelt

As required by the Institute, before the installation of the student chapter, a student chemical engineering society has been in operation for the past year.

Reported by D. S. Cryder

NORTHERN CALIFORNIA

This section held a meeting at the Engineers Club in San Francisco on June 5. Attendance was 110 members and guests. The speaker of the evening was Edward R. McCartney, assistant chief engineer (Process) for The Fluor Corp.

J. H. ROGERS
Outstanding Member, Student Chapter

Mr. McCartney described two processes which are offered by Mathieson through The Fluor Corp. Both processes produce elemental sulfur, hydrogen sulfide being the starting point in one process and acid sludge being the starting point in the other.

Because of the unusual physical and thermodynamic properties of sulfur the design of plants using the two processes presents unfamiliar problems which have to be handled by unconventional methods.

At the meeting it was announced that the executive committee selected James H. Rogers, University of California, as the outstanding member of the student chapter there to receive the section's first annual award of payment for a Junior membership in the National society.

This section held a meeting at the Engineers Club in San Francisco on May 1 with 140 members and guests in attendance. The speaker of the evening was Dr. Mott Souders, Jr., head of the chemical engineering research department, Shell Development Co. His subject was "Men, Money and Machines—the Econometrics of Venture Capital."

Reported by J. V. Hightower

CHARLESTON, W. VA.

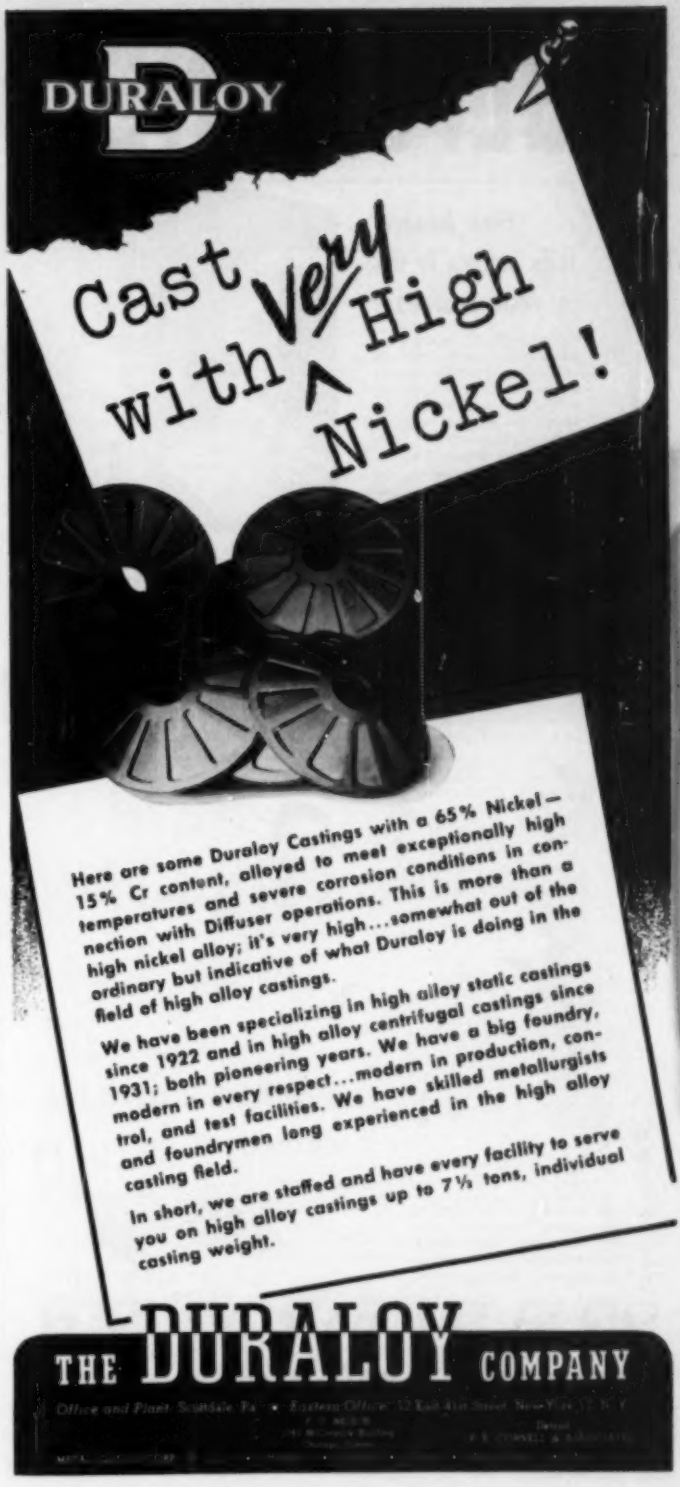
The annual business meeting and dinner of this section was held May 26 at the Kanawha Country Club.

Officers were elected for the 1950-51 season:

Chairman—A. B. Stiles—Du Dont
Vice-Chmn.—D. J. Porter—Westvaco
Secretary—M. C. Guthrie, Jr.—Du Pont
Treasurer—J. H. Howell—Carbide
Member-at-Large of Executive Committee—C. C. Richiusa—Monsanto

Following the business meeting, 134 members enjoyed the after-dinner speaker, who was W. J. Connelly, assistant director of public relations, Bakelite division, Union Carbide and Carbon Corp. His subject was "The Proper Perspective on Plastics."

Reported by R. W. King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CHEMICAL ECONOMICS HANDBOOK

(*Continued from page 24*)

During the present year, the only sheets to be issued will be new; revisions not being planned. However, as the handbook gets under way, revisions and new economic data will be issued from time to time on chemicals already covered.

Principal emphasis in 1950 will be on major industries and commodities and raw materials used by or related to the chemical industry, end chemical groups, and major chemicals.

NON-REGISTERED ENGINEERS LOSE IN PA. SUIT

Through the Chairman of the Institute's Committee on Legislation, John M. Weiss, information has been received regarding an opinion on the constitutionality of the State of Pennsylvania Engineers' Registration Law. The Supreme Court ruled on the constitutionality of this law during a case between Howarth Co. and the Gilman Manufacturing Co.

The court ruled that because the principals of Howarth & Co. were not registered engineers, they could not recover a fee from the Gilman Manufacturing Co. for services rendered. The court concluded that since the act was constitutional, Howarth & Co. had, by engaging in the practice of engineering without registering in compliance with the act, precluded themselves from recovery of the sums due under their contracts with the defendant.

The Howarth Co. had pleaded that the registration act was unconstitutional because the definition of engineering practice was vague and indefinite.

However, the court ruled that the specification of five major engineering classifications plus specific branches, was "broad enough to subject the entire field of engineering to regulation, but is, nevertheless, susceptible of a sufficiently precise interpretation and when read in the light of the purposes of the act, and in conjunction with its other sections to enable one to readily determine whether his activities are within the scope of the prohibition."

The court also ruled that a more specific definition was improbable.

BACK ISSUES WANTED

Chemical Engineering Progress is still buying the April and May issues of 1947. For these we will pay 75 cents each.

We need copies of these issues and of January, 1949, in order to supply the demand for complete volumes of back issues and also to supply the demand for complete volumes for 1949. For January, 1949, issues we will pay 50 cents.

PEOPLE

GOES TO M.C.A.

R. L. TAYLOR

Robert L. Taylor has been appointed, effective Oct. 1, to the newly created office of executive vice-president of the Manufacturing Chemists' Association, Inc. He has been editor of Chemical Industries, published by Maclean-Hunter Publishing Corp. Mr. Taylor will establish headquarters offices in New York later in the year. The present offices are in Washington, D. C.

Mr. Taylor has been engaged in publication and public relations work in the chemical industry for the past fourteen years. Following graduation in chemical engineering from the University of Michigan, he joined the editorial staff of Chemical and Metallurgical Engineering, a McGraw-Hill publication, and later served as assistant to the director of advertising and public relations of Monsanto Chemical Co. He became editor of Chemical Industries in 1943.

He is a past chairman of the New York Section and the Public Relations Committee of A.I.Ch.E.

C. DOUGLAS PORCH OF DU PONT RETIRES

C. Douglas Porch, president of Kinetic Chemicals, Inc., long a Du Pont Co.'s affiliate, will retire July 31. Mr. Porch has been with Du Pont and Kinetic Chemicals for more than 43 years.

President of Kinetic since June, 1943, and its vice-president for 13 years prior to that time, Mr. Porch went to Du Pont Co. immediately following his graduation from Princeton University in 1907 where he received a B.S. in chemistry. Early in his career he worked on the development of sulfuric acid and nitric acid recovery units and on nitric acid manufacture. Subsequently through many advances he became assistant manager and manager of the production division of the dyestuffs department.

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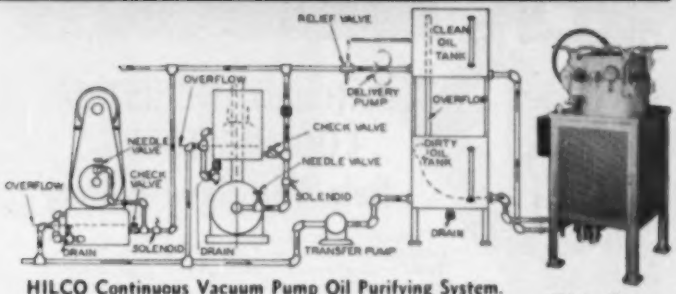

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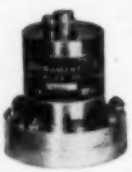

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HERNDON, LENHER, KIRK IN DU PONT CHANGES

John M. Herndon, assistant manager of the Chambers Works, Deepwater Point, N. J., has been named director of manufacture of the Du Pont Co.'s organic chemicals department. He succeeded on June 15 Samuel Lenher, who on the same date became the department's new assistant general manager. Dr. Lenher was appointed to succeed William Kirk, who is retiring.

Dr. Herndon, before going to Chambers Works, was production manager of the department's petroleum chemicals division. He went to the Du Pont Co. from Pennsylvania State College in 1933, the year in which he received his Ph.D. degree there.

Starting as a research chemist in the Jackson Laboratory at Deepwater Point, he has served as chief supervisor of the tetraethyl lead area at the Chambers Works, production manager of the tetraethyl lead division, petroleum chemicals production manager and assistant Chambers Works manager.

William Kirk, assistant general manager of the Du Pont Co.'s organic chemicals department, plans to retire at the end of the year. He has served Du Pont for 34 years. He relinquished his administrative post June 15, but until Jan. 1 will continue in the department as adviser to the general manager.

Dr. Kirk went to Du Pont in 1916 shortly after receiving his Ph.D. degree in chemistry at Cornell University. Except for a year and nine months spent at the start of his career in the explosives department's Eastern Laboratory at Gibbstown, N. J., Dr. Kirk's work with Du Pont has been associated exclusively with dyes research and manufacture and with Du Pont's role in the development, from the dye industry, of the organic chemicals industry.

Dr. Lenher received his A.B., degree in chemistry at the University of Wisconsin and his Ph.D. in physical chemistry at the University of London. In 1929, he started with Du Pont as a chemist at the experimental station.

During his career he was research chemist at the Technical Laboratory, technical adviser to the fine chemicals division, superintendent of the development group at the Chambers Works, assistant plant manager (1944), and plant manager (1945). In October, 1946, he moved to Wilmington as director of dyes manufacture, later taking charge of manufacturing for the department.

Robert A. Buckley is now a research engineer with the Du Pont Co. in Wilmington, Del. He was previously a graduate student at the University of Wisconsin.

A.I.CH.E. MEMBERS HONORED BY COLUMBIA UNIVERSITY

T. H. CHILTON

M. C. WHITAKER

Thomas H. Chilton and Milton C. Whitaker both Active members of the American Institute of Chemical Engineers were awarded University Medals for Excellence by President Dwight D. Eisenhower at the 196th Commencement of Columbia University, June 8, 1950.

Dr. Chilton, a graduate of Columbia as Ch.E., is currently Vice-President of A.I.Ch.E. and technical director, development engineering division, engineering department, Du Pont Co., Wilmington, Del. The citation, used by Provost Grayson L. Kirk in presenting the candidate, read: "for outstanding achievements in fundamental chemical engineering research and for the practical application of these principles."

Dr. Whitaker has retired as vice-president and director of the American Cyanamid Co. and is now acting as consultant for Cyanamid. He was Vice-President of A.I.Ch.E. in 1912-13 and President in 1914. He received a B.S. and M.S. from the University of Colorado, and D. Chem. Eng. from the University of Pittsburgh. He was professor of chemical engineering at Columbia from 1910-17, and received the Perkin Medal in 1923. He returned to private industry and the citation read: "for a career of more than three decades of distinguished service as executive and consultant."

EYNON GETS STUDY LEAVE FROM MONSANTO

David L. Eynon, Jr., of St. Louis has been granted leave of absence by the Monsanto Chemical Co. to attend the Advanced Management Program at Harvard University Graduate School of Business Administration. He will enroll in the 13-week program in September.

Mr. Eynon is assistant general manager of the company's organic chemicals division. Mr. Eynon joined Monsanto in 1933 as a member of the Merrimac division's research department and served subsequently in various capacities in that division. During the war he was plant manager of the government-owned Longhorn Ordnance Works at Karnack, Tex., which was operated by Monsanto.

In January, 1945, Mr. Eynon became assistant to the general manager of the organic chemicals division and acting plant manager at the Nitro (W. Va.) plant. He was appointed production manager of the division Jan. 1, 1947.

Morgan M. Hoover, formerly production supervisor with the American Cyanamid Co., Piney River, Va., is now an assistant editor on Chemical Engineering, a McGraw-Hill publication.

Luther B. Bullock, formerly a research assistant in the department of chemical engineering at the Oklahoma A. and M. College, Stillwater, Okla., is now in the research department of the Monsanto Chemical Co., Texas City, Tex.

O. C. Jones, group leader in Monsanto Chemical Co.'s phosphate division research department at Anniston, Ala., has been appointed assistant research director of the company's Western division (Seattle).

His research studies have been primarily concerned with phosphorus production, by-product utilization, and phosphoric acid.

William V. Bauer is now assistant director of development with the Stauffer Chemical Co., New York, N. Y. He was formerly chief process engineer.

C. E. Kenneth Mees, vice-president in charge of research of the Eastman Kodak Co., Rochester, N. Y., received an honorary doctor of science degree from the Alfred University on June 11. It was conferred by Dr. M. Ellis Drake, president of the university. Dr. Mees gave an address entitled, "Technology and Education."

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SITUATIONS OPEN

Supervising Chemical Engineer — Chemical Engineering Degree, preferably Ph.D. 35 to 45 years of age. Approximately 15 years' experience in organic chemical industries, preferably intermediates or dyestuffs. Thoroughly experienced in applying chemical engineering principles to production problems in batch process type of industry. Permanent position in well-established company in upstate New York. Send complete business resume and salary requirements. All replies confidential. Box 1-7.

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Chemical Engineer — Graduate, with five years' chemical manufacturing experience to join engineering staff of large insurance company. Good contact personality essential. A.I.Ch.E. membership desirable. Give all personal data and salary requirements in first letter. Box 13-7.

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A.I.Ch.E. Members

Teaching and Research—Ph.D. in Ch.E. Active member A.I.Ch.E. Five years' industrial experience and two years as assistant professor in accredited Ch.E. department. Undergraduate and graduate courses. Thesis and sponsored research supervision. Box 2-7.

Chemical Engineer—B.S. 1942, also B.A., Business Administration. Seven years' excellent experience in industrial engineering and production control for chemical operations. Desire position requiring technical-administrative ability. Box 3-7.

Chemical Engineer—B. E. 1948, M.S. in Chem. Eng. 1950; single, 24. Two and one-half years' experience in plastics research and development in laminates and molded products. Desire position in research-developmental work. Preferred location, eastern U. S. Excellent references. Box 4-7.

Chemical Engineer—B.Ch.E. 1947, veteran, 30, family. Three years' experience pilot plant research and development including supervision and operations. Two years' experience analytical laboratory. Desire position affording continued opportunity; responsibility. N. Y.-N. J. area preferred. Box 5-7.

Sales and Service Engineer—B.S.Ch.E. Case, 1948. Engr.-in-Trng., Ohio. Single, 26. Traveled two years for large chemical firm contacting industrial accounts selling service. Charge of 2-3 man crew. Desire relocation Cleveland or N. Ohio. Box 6-7.

Plant Design Group Leader—B.Ch.E., registered, Tau Beta Pi, 24. Six years with research organization in design, cost estimation, purchase and installation of solvent extraction process equipment and pilot plants; some operations. Excellent references. Box 7-7.

Chemical Engineer—B.S.Ch.E., age 28, married, family. Two years U. S. Navy. Five years' experience in industry, process and development engineering, inorganic chemicals. Desire position with future in management or engineering. Box 8-7.

Chemical Engineer—31, R.P.I. 1940. Seven years' diversified production and engineering experience large chemical corporation plus three years complete management small chemical company. Box 9-7.

Chemical Engineer — Conscientious, ambitious, wishes change to more responsible position with opportunity for advancement. 7½ years' experience research department of major company; polymer development, pilot plant design and operation, production - engineering - research liaison, etc. Box 10-7.

Chemical Engineer—29, single, B.Ch.E. degree. Approximately three years' experience in HF manufacturing, processing, development, and data compilation. Experience in modern contact sulfuric plant; steam and water treatment. Desire responsible engineering work. Box 11-7.

Plant Engineer—B.S., 30. Five years in operation, design, construction and maintenance of petroleum chemical plants. Three years Navy engineering officer. Desire plant engineering position, location immaterial. Box 12-7.

Teacher of Chemical Engineering — Ph.D. June, 1950; single, 25. Good background fluid flow, chemical thermodynamics and kinetics, gas absorption and mathematics. Desire teaching position with opportunity for research. Location immaterial but prefer South or Midwest. Box 14-7.

INDUSTRIAL RESEARCH GROUP LEADER

Registered engineer. Twenty - two years' experience in guiding new projects from conception through final plant demonstration. Would prefer organizing permanent research group for medium size company. Box 15-7.

ADDED TO NORDSTROM SALES

C. J. KENTLER, JR.

Charles J. Kentler, Jr., has been appointed as applications engineer of the Nordstrom valve division of the Rockwell Manufacturing Co. Mr. Kentler's assignment will cover the chemical, petrochemical and allied industries. His headquarters will be in Pittsburgh, Pa. He was graduated in 1940 from Yale University, and received a Ph.D. degree in chemical engineering from Cornell University in 1948. He was formerly associated with Wallace & Tiernan Products Co., Belleville, N. J.

Walter H. Harte was recently put in charge of process engineering of the Minute Maid Corp., the main offices of which are in New York, N. Y. Minute Maid Corp. pioneered in the frozen citrus concentrate industry. Plants are located at Plymouth, Leesburg, and Davenport, Fla.

Fred H. Amon, technical director of Godfrey L. Cabot, Inc., carbon black manufacturing concern, recently returned from a trip to England, Scotland, France and Italy. In Birmingham and Liverpool he presented a paper on the manufacture of carbon black in England, before the Institution of Rubber Industry.

Charles Allen Thomas, executive vice-president of Monsanto Chemical Co., St. Louis, Mo., received the honorary LL.D. degree from Hobart College June 11. At the same time Dr. Thomas was made an honorary member of Phi Beta Kappa, Zeta Chapter of New York. He delivered the principal address at the 125th Commencement of Hobart which was held jointly with the 39th Commencement of William Smith College.

Thomas Whelan, Jr., has been appointed district sales manager for the Houston (Tex.) office of The Patterson Foundry & Machine Co., East Liverpool, Ohio. Mr. Whelan was formerly with C. F. Braun Co., in the design and sale of processing equipment. His headquarters will be at 2405 San Jacinto St., Houston.

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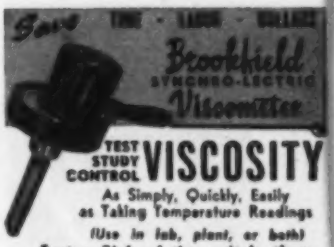

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E. V. HARLOW ADVANCED BY KOPPERS CO., INC.

Earl V. Harlow has been appointed engineering assistant to Walter F. Perkins, vice-president and general manager of the metal products division of Koppers Co., Inc.

E. V. HARLOW

Formerly associated with Koppers central research department, Mr. Harlow in his new assignment will be responsible for assisting and advising the division general manager on engineering matters, and for coordinating research and development projects between the division and the research department.

Mr. Harlow joined Koppers as a draftsman in 1926 and two years later became associated with the company's research department. From 1942 to 1946 he was chief process engineer at the Kobuta styrene and butadiene plant which Koppers built and operated for the U. S. Office of Rubber Reserve. Since 1946 Mr. Harlow has been engaged in research activities at the Seaboard Experimental Station of the research department in Kearny, N. J.

A native of Bern, Kan., Mr. Harlow was awarded a B.A. degree in physical science by the Peru State Teachers College in Peru, Neb., and later received a B.S. in chemical engineering from Carnegie Institute of Technology, Pittsburgh, Pa.

Necrology

B. A. IRWIN

Bruce A. Irwin, vice-president and general manager of the Hammel-Dahl Co., Providence, R. I., was fatally injured on June 14, 1950, in an automobile accident.

For more than 20 years, he was actively engaged in the design and development of automatic flow control in the chemical, petroleum and process industries. He has been associated with the Hammel-Dahl Co., diaphragm control valve manufacturers, since 1946, in the capacity herein named.

During the war years he was secretary of the materials co-ordinating committee of the Petroleum Administration and was chief of the P.A.W. materials requirements section.

Mr. Irwin was a member of the Instrument Society of America, and other technical societies. He was 48 years old and was a graduate of the University of Michigan (1923).

WILLIS F. WASHBURN

Willis F. Washburn, 64, a chemical engineer in many fields and an important figure in the paint industry, died recently at Waterville, Me. His contribution to the paint industry was first made when he served as professor of industrial chemistry at North Dakota Agricultural College and later on the improvement in the manufacture of titanium pigments. During World War I he served as a Captain in the Chemical Warfare Service, was active in the building and operation of a plant to make war gases. Later in life he practiced as a consulting chemical engineer until his retirement. Mr. Washburn was born in China, Me. He graduated from the University of Maine in 1907 and took his M.S. there in 1909. He was a member of several technical societies.

THOMAS COLE MAIN

Thomas C. Main, who was associated with the Wyatt C. Hedrick Engineering Corp. as chief process engineer, died in San Antonio, Tex., recently. He was at one time affiliated with the research department of the Celanese Corp., Beaumont, Tex.

A. H. WINHEIM

Adolph Herbert Winheim, 44, head of the Planetary Chemical Co., Creve Coeur, Mo., was killed June 3 in an automobile accident. As president of the American Leather Chemists' Association he had attended the three-day convention of that association in French Lick, Ind., and was returning to St. Louis, it was reported.

Mr. Winheim was also vice-president of International Leather Chemicals, Inc. Before going into business for himself in 1946, manufacturing chemicals for the leather industry, insecticides and other chemical products, he worked for International Shoe Co. as a chemist. He was associated at one time with the Quaker City Tank Line Co., Fouke Fur Co., as chemist, and with the Whitex Chemical Co. Mr. Winheim was graduated from Washington University in 1927 with a B.S. in chemical engineering.

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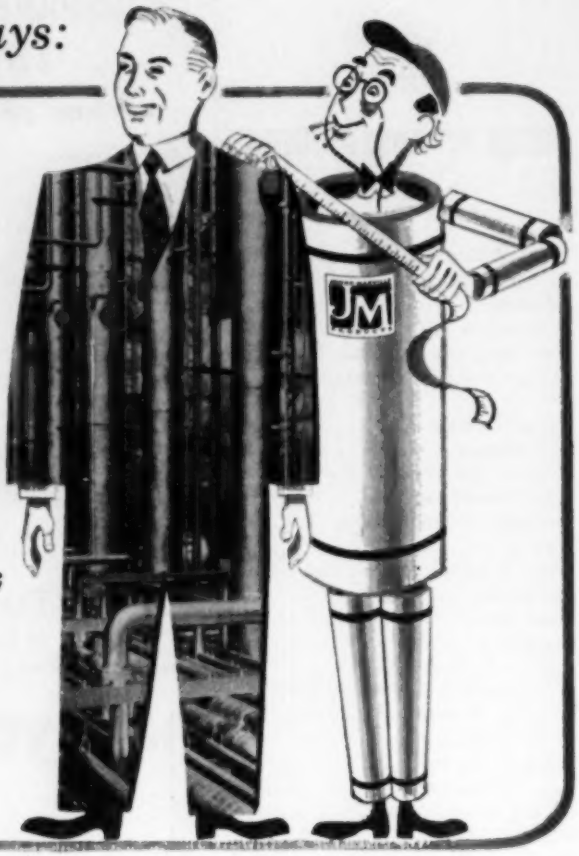

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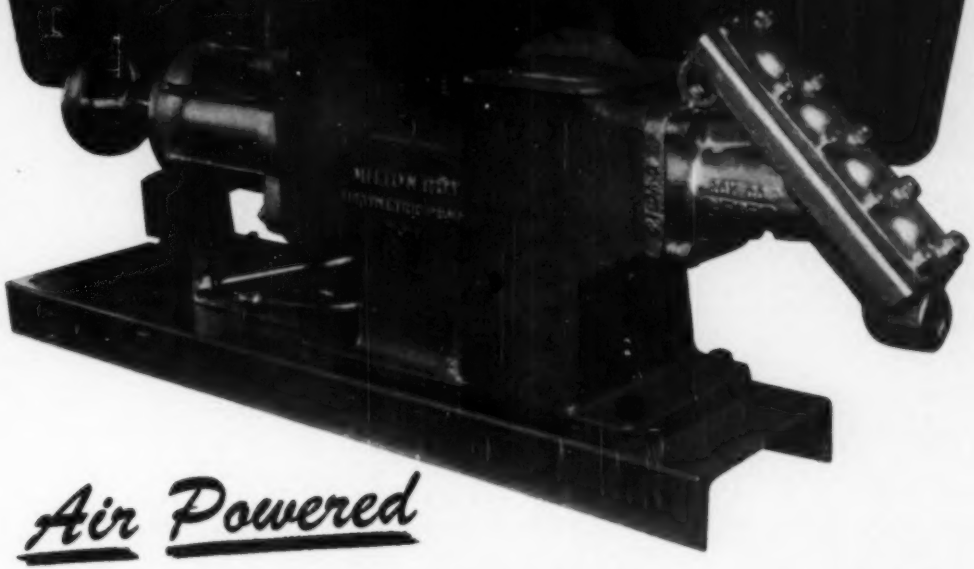

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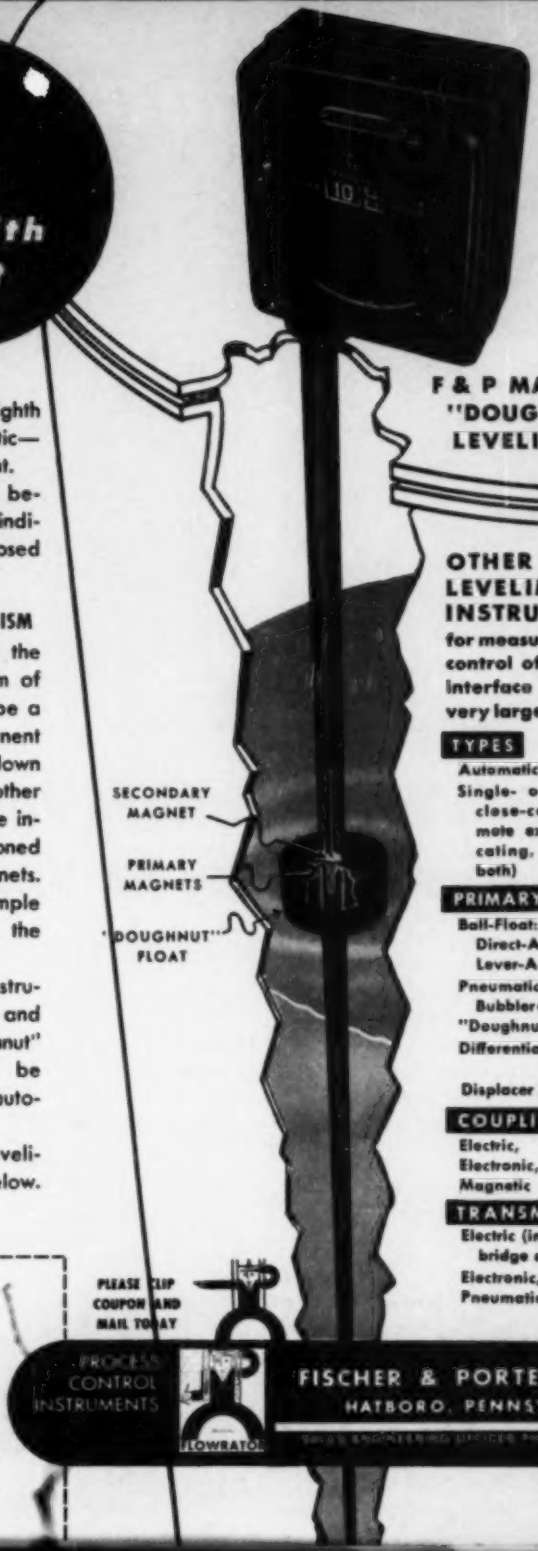

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